Performance of Epoxy-Injected Concrete in Hot Weather Conditions

by

Hossam Salah Eldin Khalil

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

CIVIL ENGINEERING

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بسم الله الرحمن الرحيم

In the name of Allah, the Beneficient, the Merciful

بسم الله الرحمن الرحيم

"وَقُل رَّبِّ زِدْنِي عِلْماً"

(طه - ١١٤)

In the name of Allah, the Beneficient, the Merciful

"And say : My Lord ! Increase me in knowledge !"

(Taha - 114)

This thesis
is dedicated
as a humble tribute
to my parents and sister
for their sacrifice
to educate me

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التخصـــــص : هندسة مدنية

تاريخ الدرجــة : يناير ١٩٨٩م

تتعرض منطقة الخليج العربي لعوامل مناخية قاسية . وقد أدت مستويات الرطوبة والمصاحبة للتغيرات الفصلية واليومية في درجة الحرارة الى تآكل وتشقق كثير من المنشآت الخرسانية بسرعة . وتستخدم حاليا المواد الصمغية الابوكسية بكثرة في علاج مثل هذه الوحدات الخرسانية المتشققة . ولكن لاتوجد معطيات حالية عن مستوى أداء هذه المواد الابوكسية المستخدمة تحت ظروف المناخ الشديدة في منطقة الخليج. وهذا مما يجعل عوامل الاختيار أكثر صعوبة في ظل الأعداد الهائلة من هذه المواد والمتوفرة في السوق المحلي .

وقد أجريت هذه الدراسة لعلاج هذا الموضوع ، وذلك عن طريق أداء برنامج تجارب معملي تحت ظروف مماثلة لعوامل الجو الطبيعية . وتم استخدام مجموعات من العينات الأسطوانية الخرسانية لهذا الغرض ، ويبلغ قطر العينة منها ٢ر٧٦ مم (٣ بوصة) وارتفاعها ٤ر١٥٢ مم (٦ بوصة) وتحتوي على شق اصطناعي مائل بزاوية قدرها ٣٠ مع الخط الرأسي وبسمك مقداره ٦ر١ مم ($\frac{1}{16}$ بوصة) . وقد أستخدمت ثلاثة أنواع من المواد الابوكسية المتوفرة في السوق المحلي في حقن الشقوق في هذه العينات . وبعد فترة المعالجة تم تعريض العينات الأسطوانية لثلاثة عوامل مناخية مختلفة وهي : درجة حرارة ٧٠° مئوية (١٥٨° فهرنهايت) ، برنامج دورات تسخين وتبريد ، برنامج دورات ترطيب وتجفيف . وتلا ذلك اختبار هذه العينات تحت الضغط حيث تعرضت قوة التلاصق بين الابوكسي والخرسانة الى قوتي الضغط والقص معا . وبنفس الأسلوب أستخدمت مجموعات من العينات الكمرية الخرسانية ، تبلغ أبعاد العينة منها ٤ر١٥٢ مم × ٤ر١٥٢ مم × ٤ر٥٣٣ مم (٦ بوصة ×٦ بوصة × ٢١ بوصة) وتحتوي على شق اصطناعي في المنتصف بسمك قدره ٦ر١ مم ($\frac{1}{16}$ بوصة) ويمتد في نطاق الشد للعينة الكمرية . حقنت هذه العينات بنفس المواد الابوكسية ثم تعرضت الى عاملي درجة الحرارة العالية وبرنامج دورات التسخين والتبريد ثم أختبرت باستخدام اختبار الانثناء حيث كانت قوة التلاصق بين الابوكسي والخرسانة معرضة لقوة الشد في هذه

أوضحت نتائج هذه الدراسة أن عوامل المناخ المذكورة لها تأثير هام وضار على قوة التلاصق بين المواد الابوكسية والخرسانة ومن ثم على قوة صلابة وتحمل الخرسانة المعالجة بهذه المواد . وقد أبدت المواد الابوكسية المستخدمة في هذه الدراسة بعض الفروقات في مستوى الأداء تحت هذه الظروف المناخية . وكان التغير في خواص هذه المواد عند درجات الحرارة العالية والفرق الكبير في معامل التمدد الحراري بين هذه المواد والخرسانة وكذلك الفرق في التغيرات الحجمية بينها وبين الخرسانة نتيجة لحركة الرطوبة من والى هذه الخرسانة المعالجة من أهم الأسباب لهذا التدهور . وبناء على ذلك ينبغي استخدام مواد الأبوكسي المعدة خصيصا للاستخدام في مثل ظروف منطقة الخليج العربي في حقن ومعالجة المنشآت الخرسانية في تلك المنطقة .

درجة الماجستير في العلوم

جامعة الملك فهد للبترول والمعادن

الظهران - المملكة العربية السعودية

يناير ١٩٨٩م

ABSTRACT

The Arabian Gulf region is characterized by severe weather conditions. The high humidity levels coupled with large diurnal and seasonal temperature variations resulted in rapid deterioration and cracking of many concrete structures. Currently, epoxies are increasingly being used in the repair of such cracked concrete elements. However, presently there is no data available on the field performance of such epoxy resins in the harsh environmental conditions of the Gulf region. This makes the selection criteria rather difficult in view of the enormous number of resins available in the local market.

This present study was made to address this issue by running an experimental program in the laboratory under simulated conditions to those of the actual environment. Concrete cylinders, each of 76.2 mm (3 in) diameter and 152.4 mm (6 in) height with a slant gap (simulated crack) of 30^0 angle from vertical and of 1.6 mm (1/16 in) thickness, were epoxy injected using three of the locally available commercial epoxy products. After curing they were exposed to three different environmental conditions, namely a high temperature condition of 70^0C (158^0F), a heat-cool cycling program and a wet-dry cycling program, and then tested in compression, where the bond between epoxy and concrete was subjected to combined compressive and shear stresses. Similarly, concrete beams of dimensions 152.4

mm x 152.4 mm x 533.4 mm (6 in x 6 in x 21 in) with a crack in the middle of each beam simulated by a pre-inserted notch of 1.6 mm (1/16 in) thickness running in the tension zone of the beam were epoxy injected with the same epoxy compounds, exposed to the high temperature condition and the heat-cool cycling program and then tested in flexure where the bond between epoxy and concrete was subjected to linear tensile stresses.

Results of this work showed that these environmental factors have a considerable detrimental effect on the epoxy-concrete bond, and therefore, on the strength and durability of repaired concrete elements. The epoxy compounds used showed some variation in their performance under these conditions. The change in their properties at high temperatures, the large difference between their coefficients of thermal expansion and that of concrete and the difference in volume changes between these epoxies and concrete due to the moisture movement into and from the repaired concrete were the main causes of this degradation. Properly formulated epoxies to suit the conditions of the Gulf region should be used in the repair of structures in this region.

Chapter 1

INTRODUCTION

1.1 General

The vast and rapid pace of construction that took place in the Arabian Gulf region over the past two decades offered little or no opportunity for engineers and architects to study and carefully examine the long term effect of the region's harsh environmental factors on the durability and performance of most structures. The high humidity levels coupled with large diurnal and seasonal temperature variations have resulted in rapid deterioration and cracking of many concrete structures. Currently, epoxies are increasingly being used in the repair of cracked concrete elements. They tend to restore the architectural and structural integrity of these elements by sealing the cracks and restoring the strength characteristics. However, presently there is no data available on the field performance of such epoxy resins in the harsh environmental conditions of the Gulf region. This makes the selection criteria rather difficult in view of the enormous number and variety of resins available in the local market. The present study is to address this issue.

Chapter One provides a brief introduction on the repair of reinforced concrete structures with more emphasis on epoxy resins and crack injection. Chapter Two includes the literature review and laying down of the objectives and scope of the study. The experimental program of this study is detailed in Chapter Three, and followed by the analysis of data and discussion of results in Chapter Four. Finally, summary, conclusions and recommendations of the study are listed in the Fifth Chapter of this thesis.

1.2 Role of Repair in Reinforced Concrete Structures

The use of reinforced concrete as a structural material for construction has gained its prominence in the early twentieth century and there are now many millions of concrete structures worldwide. Although the durability record of such structures is fairly good, damage to some structures may be caused by a variety of reasons. Premature damage to concrete structures may be due to lack of proper design or construction, inferior quality of constituent materials, and/or exposure to severe environmental conditions. Physical damage can result from overloading, subsidence, impact or fire. [3-5].

Repair of damaged concrete structures provides, in most cases, an economic means to restore their original conditions. There are different repair materials and techniques, which suit different types of damaged components. In general, the first step in the repair process is the diagnosis of the problem and determination of the various contributing factors. The next step is to eliminate or reduce the effects of these factors and apply repair to the damaged areas of the structure. The last step is to provide protection for the repaired areas as well as the other parts of the structure against future reoccurance of such damage. [3-5].

For example, steel in concrete is protected from corrosion by the presence of alkalis released from the process of cement hydration, and providing those alkalis remain intact, steel protection against corrosion is assured. However, concrete is permeable to both gases and water, and the ingress of carbon dioxide into the hydrated cement matrix will lead to neutralization of the alkalinity with consequent loss of protection, and hence, corrosion of steel (in the presence of enough oxygen and water). Normally, concrete is specified such that the process of alkali neutralization (known as carbonation) does not progress to full depth of cover during the life time of the structure, but improperly mixed concrete or misplaced steel lower than the specified cover would instigate faster carbonation leading probably to corrosion. Reinforcement may also be put at risk due to the presence of aggressive materials in concrete, chlorides being the most critical of agents which stimulate steel corrosion. Chlorides may be introduced to concrete through the use of chloride-based set accelerators, through the contamination of concrete mix materials, through exposure to environment in marine location, or through exposure to chloride-based de-icing salts. When the concrete contains considerable amounts of chlorides, careful considerations should be taken for the feasibility and type of repair chosen. Therefore, in order to have an effective repair, it should provide enough protection to the steel from the ingress of chlorides contained in the nearby uncracked original concrete. Additionally, the remaining concrete should be protected from these factors by, for example, applying a protective coating, which prevents the penetration of such materials, and remains compatible with the substrate. These requirements together with the durability requirements under the exposure to the environment, define the performance need of a concrete repair system [3].

The term "repair system" involves a number of different components including coats to both reinforcement and concrete substrate, patching material and any coating material to finish the repair. Although repair systems differ in formulation and mode of protection, the properties and functions of the elements of repair systems are, in general, common. Bonding coats are required to provide enough protection against rebar corrosion and good bond between the applied patch material and the underlying substrate. Patch materials are required to have dimensional stability relative to the substrate as well as to develop sufficient mechanical strength, if needed, and provide enough protection to the underlying steel reinforcement without being deteriorated under exposure to the surrounding environment. Likewise, surface coatings applied for appearance and protection are required to be stable, flexible, having good adhesion to substrate, and retaining their properties against the ingress of deleterious materials and against weathering [3].

Good surface preparation is necessary before applying repair materials. That includes the removal of any dust, laitance, and loose and deteriorated concrete until only sound concrete is exposed, and it also requires that reinforcement is thoroughly cleaned from scale, loose rust, or any contamination that might interfere with bond. Applying repair materials should be strictly in accordance with the manufacturer's instructions. Finally, it is desirable for a successful repair work to be carried out by experienced operators who fully understand the reasons behind the techniques that are being used [4].

1.3 Use of Epoxy Compounds with Concrete

1.3.1 Merits and Demerits of Epoxies

Epoxy adhesives represent a wide range of chemical polymers with extremely diverse chemical, thermal and mechanical properties. Epoxy resins are derived from the intermediate products of the oil refining process. The mixing of the epoxy resins with the designed amount of hardener results in an epoxy adhesive with a predetermined pot life [34]. There are many characteristics of epoxies and their uses which make them a desirable adhesive for use with concrete [6]. Some of these advantages are:

1) Epoxy resins have excellent adhesive qualities and will bond to nearly all construction materials.
2) The wide range of available physical and chemical characteristics of epoxy resins make them required in different situations involving repair, overlay, coating, or adverse environment of concrete. The variety of curing agents, extenders, diluents, fillers, and other modifiers permit the formulator to attain special characteristics for any particular application.
3) Compared to other thermosetting plastics, epoxies have very low autogenous shrinkage. Formulations are available in order to have an effective shrinkage during curing as low as 0.001 percent.
4) The system of epoxy resin and hardener can be cured (changed from the liquid state to the solid state) within a matter of few minutes and the time can be extended several hours by changing the system.
5) Epoxies are characterized by high mechanical strength.
6) Epoxies are highly resistant to the attack of acids, oils, alkalis, and solvents.
7) A thin coating of epoxy can make the surface impermeable to water even when continuously inundated.
8) They have excellent abrasion resistance.

The benefits of using epoxies are noteworthy, but caution must be exercised [6]. Some of the precautions to be considered are:

1) Strain Compatibility: Epoxy bonds very rapidly to a concrete surface and within a short period of time may be an entity therewith. The autogenous shrinkage strains which take place in some epoxy formulations can cause severe strains at the bond line and when combined with thermal strains contributes significantly to delamination, generally by failure in the top 6mm (¼ in.) of concrete interface. Also, there is a large difference in the coefficients of thermal expansion of concrete and cured epoxy, and that may lead to delamination. Filling the epoxy compound with some fillers such as silica reduces the difference in the coefficients in proportion to the amount of fillers used. Using a flexible epoxy compound will allow the system to adjust for the variation in the thermal coefficients of expansion.

2) Thermosetting Plastics: The components must be mixed thoroughly and a control of temperature before, during, and after application is necessary to assure there is enough heat for epoxy to cure in a given time. Once it is cured, it will not melt. However, some epoxies loose some of their elasticity at higher temperatures and become cheesy since their mechanical properties change significantly beyond their heat distortion temperature (HDT). The HDT is different for each formulation, and for those epoxies used in

construction it ranges from 15° to 65° C (60° to 150° F).

These precautions can be satisfied by a proper selection of the epoxy compound formulation based on considerable study of all application restrictions and requirements involved. It is unwise to depend on general specifications or general performance criteria in choosing the epoxy compound used [6].

Epoxies are presently used with concrete in the form of coatings, repair materials, grouts, bonding agents, paints, adhesives, epoxy mortars and concrete, seal coats and wearing surfaces. The volume of applied epoxies has been increasing leading to lower cost and better performance for these materials [6].

1.3.2 Components of an Epoxy System

Success of epoxy compounds in different applications is dependent on formulating the package into a two-pack composition with suitable materials. These materials include the resin itself, the diluent or modifier, the hardeners and accelerators, and the fillers/aggregates. Epoxy resins by themselves have no practical use and in order to convert them into useful materials it is necessary for them to react with a suitable curing agent or hardener. Therefore, the basic performance of an epoxy compound depends on the type of resin, hardener agent, and the diluent used, these three components are referred to as the binder system. The most frequently used resins in civil engineering are the Bisphenol-A type liquid epoxy resins. Usually, blends of resins are prepared in order to obtain certain properties such as resistance to crystallization (solidification) during storage, lower viscosity to enable higher filler loading, and overall higher performance. Blends of Bisphenol-A and Bisphenol-F resins are typical examples. The structures of these resins are shown in Fig. 1.1 [7].

1.3.2.1 Characterization of Epoxy Resins

Epoxy resins are characterized by a series of tests carried out at the time of production. These tests are relatively simple and seek to provide a description of properties and performance of these resins. A typical material specification will contain such properties as epoxide equivalent weight (or percentage epoxide), melting point, viscosity, colour and density. The epoxide equivalent weight (EEW) is fundamental in quantifying the properties of epoxy resins. It determines how many grams of epoxy resins are needed to contain one equivalent of epoxy groups (1 equivalent of epoxy groups = 43 grams). For example, if the EEW for an epoxy resin is equal to 200, that means 200 grams of this epoxy resin contains one gram equivalent of epoxide group, i.e. 43 grams. The higher the EEW, the higher its molecular weight and the lower its reactivity. The relations between EEW and some of the physical properties of epoxy resins are shown in Fig. 1.2 [7].

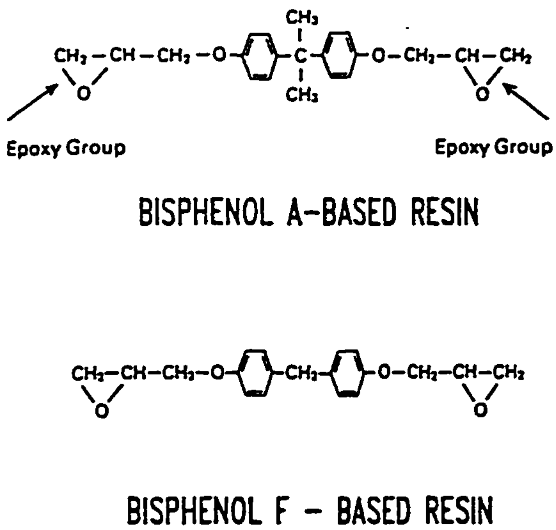


Fig. 1.1: Various Types of Epoxy Resins
Source: Reference [7].

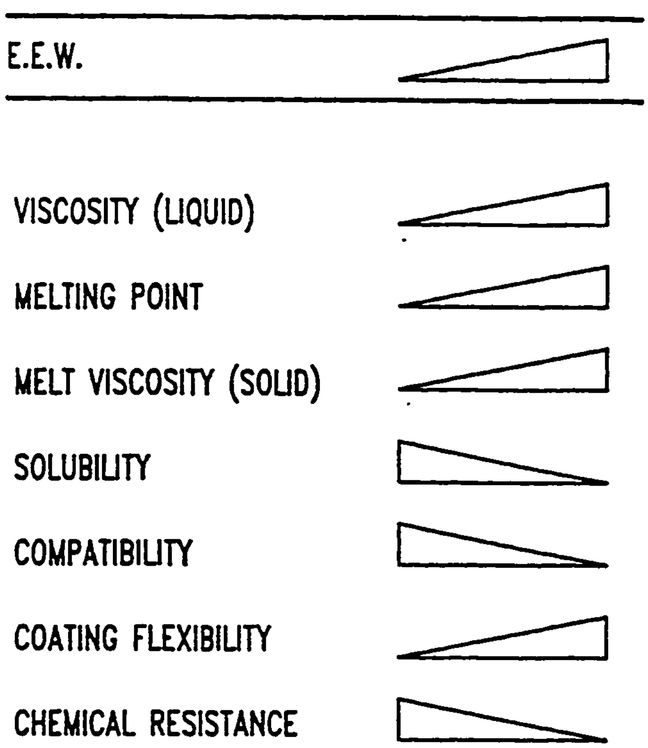


Fig. 1.2: Influence of Epoxide Equivalent Weight on Resin and Coating Properties. Source: Reference [7]

1.3.2.2 Diluents for Epoxy Resins

An alternative way to blending different types of epoxy resins is to use a standard type of epoxy resins and incorporate a diluent into its formulation in order to reduce viscosity. Diluents which are used in epoxy formulation are either reactive or non-reactive. Reactive diluents are chemical compounds that contain one or at most two epoxide groups. They are low viscosity liquids and completely compatible with the epoxy resin. Reactive diluents have an advantage over solvents which are also used to reduce viscosity; their epoxy functionality allows them to react into the final system. Reactive diluents are added to liquid epoxy resins by a blending operation, and the ratio of resin to diluent depends on the end-use. Non-reactive diluents have different characteristics and can therefore affect the properties of the end product performance. Although they may reduce some properties such as chemical resistance, other characteristics may be improved. A significant increase in impact resistance and flexibility may be highly desirable in certain applications [7].

1.3.2.3 Hardeners for Epoxy Resins

Epoxy resins must be mixed with hardeners (curing agents) before use. The ratio of hardener to resin is important because the end product should not contain any excess of unreacted resin or hardener. The choice of hardener is as important as that of the resin itself. Hardeners affect the following properties particularly:

Reactivity: Very reactive curing agents will react very fast with epoxy resins leading to a short pot life. Therefore, without careful selection of the degree of reactivity of the hardener, or proper control of the ambient temperature, the epoxy resin system may gel before it is fully applied resulting in wastage and possibly weak workmanship.

Viscosity: Hardeners of very low viscosity will reduce the overall viscosity of the epoxy resin system and that can facilitate sprayability, brushability, or the addition of more filler into the formulation of the system. In contrast, curing agents of high viscosity may prevent the system from dripping or sagging when applied to a vertical surface.

Performance: Similar to resins, hardeners may contain one, two, three, or more reactive sites in their molecular structure. More reactive sites will produce a tighter three-dimensional molecular network when fully reacted. That may affect some of the properties positively like chemical resistance and the heat distortion temperature, but not necessarily the mechanical properties such as failure strains.

Typical hardener classifications used in civil engineering formulations include:

- aliphatic amines
- aliphatic amine adducts

- cycloaliphatic amine adducts
- accelerated aromatic amine adducts, and
- polyamides

There are many individual products and blends within each of these groups. Usually, their exact formulation is a proprietary information and not disclosed [7].

1.3.2.4 <u>Fillers for Epoxy Resins</u>

There is a wide variety of fillers that are used with resins, the choices and quality of them depends on the end use, economics, and availability. Fillers are added to the epoxy resin system to change or obtain a desirable property in the system. They are also important to reduce costs and enable the use of epoxy resins, which would not otherwise be feasible as in the case of resin based mortar system, for example.

The following characteristics are influenced by the use of fillers:

<u>Pot Life and Exotherm</u>: An increase in the pot life of the system and reduction in the exotherm temperature is expected from the addition of fillers, since they reduce the concentration of the reactants and absorb heat evolving from the exothermic reaction during the epoxy curing.

Thermal Shock Resistance and the Coefficient of Thermal Expansion: Excessive thermal expansion of resin systems may be detrimental to their performance because of the risk of delamination between the coating and the subsurface. Resin systems have coefficients of thermal expansion of around 6-8 times that of concrete and with the addition of fillers they can be reduced to 2-4 times the coefficient of thermal expansion of concrete. The latter expansion can normally be accommodated.

Workability: It is fundamental to the ease of application of mortars for floorings, grouts, repair formulations, etc.

Factors affecting the choice of filler for epoxy formulation include the chemical composition, size and shape. The following are some points which are relevant to the epoxy formulation and can help in the selection of the suitable filler:

- Spherical aggregates give higher mechanical performance.
- Angular aggregates improve the ease of troweling.
- The maximum particle size should not exceed one-third of the recommended coating thickness.
- The filler should obtain graded particles upto the maximum size for optimum performance.
- Including a proportion of very fine particles (less than 0.1mm) in the mix will improve workability.

A typical particle size gradation of a filler for an epoxy mortar is shown in Table 1.1. Considerable experience is required to provide a system which will be easy to apply and give reproducible results. This type of information is normally kept proprietary, and is a part of the technology package offered by an experienced formulator [7].

Combining epoxy resins of different epoxy equivalent weights (EEW), type, and reactivity with chemically different curing agents, diluents and fillers allow the formulation of a two-component epoxy resin systems for use in different civil engineering applications. Achieving the best performance from all of these individual components requires a high degree of skill in epoxy resin technology, system rheology, and engineering mechanics [7].

1.3.3 Chemical and Physical Characteristics of Epoxy Resins

Some of the important characteristics of epoxy resin systems [6] are as follows:

i) Adhesion Properties: Epoxies bond very well to almost all materials provided that an appropriate surface preparation has been given. There are tests for adhesion which can be utilized to check the surface conditions of concrete. Some of the factors that make epoxies good adhesives are:

(a) They can be in liquid form and yet contain no vol-

Table 1.1: Typical Filler Grading for Use in Epoxy Mortar

Sieve Mesh (mm)	RETAINED (%)
2.0	0
1.5	10
1.0	30
0.5	55
0.1	90

atile solvent.

(b) They adhere to most materials used in construction.

(c) No by-products are generated during cure.

(d) Curing Shrinkage is low.

(e) Long time dimensional stability is good.

(f) They have high tensile and compressive strength.

(g) Appropriate formulations are resistant to moisture, alkalis, and most environmental factors.

ii) Mechanical Properties: Table 1.2 shows a comparison between epoxy systems and concrete in some of the mechanical properties, where epoxy tensile strength and elongation are values at the time of rupture. However, even highly elongating epoxies may have negligible stretch when highly filled. Therefore, it is important that the compound be used as the manufacture advises.

Epoxy resins react upon combination to form a thermosetting plastic which does not melt. Their properties after curing are generally satisfactory upto a temperature of 66.5°C (150°F). At higher temperature the properties change adversely, and above 300°C (572°F) the resin will change and generally volatilize, the fumes from which may be toxic.

iii) Susceptibility to Chemical Attack: Generally,, epoxies are resistant to chemical attack. A general comparison with concrete is given in Table 1.3. Epoxy systems

Table 1.2: Comparative Mechanical Properties of Epoxy Systems and Concrete

Properties	Flexural Strength psi (kgf/cm^2)	Tensile Strength psi (kgf/cm^2)	Compressive Strength psi (kgf/cm^2)	Elongation Percent
Structural Concrete (typical)	500-1000 (35-76)	300-700 (21-49)	3000-10,000 (211-703)	0.01
Epoxy Compounds (typical)	1500-5000 (105-351)	500-5000 (35-351)	500-12,000 (35-843)	0.2-50

Table 1.3: Chemical Properties of Epoxy and Concrete

Properties	Epoxy	Concrete
Wet-dry cycling	Excellent	Excellent
Chloride deicing salts	Excellent	Fair
Muriatic acid (15 percent HCL)	Excellent	Poor
Foods acids (dilute)	Good	Poor
Sugar solutions	Excellent	Fair
Gasoline	Excellent	Excellent
Oil	Excellent	Excellent
Detergent-cleaning solutions	Excellent	Excellent
Alkalis	Excellent	Good
Sulphate	Excellent	Fair

used to protect concrete from food spillage must be compounded for specific end uses. Type and concentration of existing acids as well as the temperatures available are important considerations in the selection of the proper epoxy compounds.

iv) Electrical Properties: Epoxies are excellent electrical insulators. There are some techniques which enable epoxies to conduct or partially conduct electricity. Such property, for example, may be needed in operating room floor surfacings in hospitals.

v) Abrasion Resistance: Epoxy compounds can be formulated to withstand severe abrasion, but conditions of use have to be well understood in order to select the most proper epoxy formulation. Whether the surface is hot or cold, wet or dry, and the type of abrasion are examples for the surface conditions that must be known for an optimum result from epoxy application.

vi) Resilience: Epoxies can undergo considerable deformations, and return back to their original conditions, provided that they do not exceed their elastic limit.

vii) Creep and Relaxation: Epoxies exhibit creep and also relaxation. Therefore, both advantages and disadvantages of these properties should be considered for each application.

viii) Thermal Expansion: Steel and concrete have similar thermal expansion, and therefore when combined as reinforced concrete, they do not cause a problem either in design or use. On the other hand, epoxy and concrete have major difference in their coefficients of thermal expansion as shown in Fig. 1.3, and that requires careful considerations when using epoxy compounds with concrete.

This effect can be clarified, in a exaggerated manner, by looking into Fig. 1.4a, where (a) is a slab of concrete surfaced with an epoxy (b). Due to the difference in coefficients of thermal expansion and as the temperature rises, (b) will tend to grow larger that (a), and if concrete was as elastic as the epoxy, the result would be shown in Fig. 1.4b. Conversely, if temperature drops, (b) will shrink more than (a) resulting in the deformation shown in Fig. 1.4c.

Concrete has a high modulus of elasticity, and therefore, it tends to restrain the movement of epoxy thereby causing severe stresses at the interface due to temperature changes. Epoxy yields under stresses, and if properly formulated, it can accommodate relatively large dimensional changes resulting from thermal effect. Also the coefficient of thermal expansion can be reduced considerably by the addition of filler as in Fig. 1.3.

ix) <u>Exotherm Developed During Cure</u>: Epoxies produce an

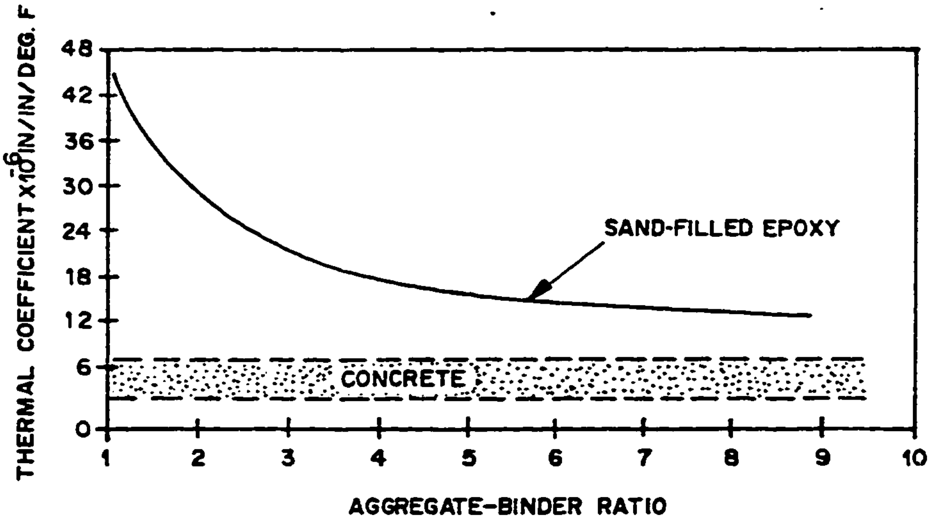


Fig. 1.3: The Effect of Changes in the Sand Aggregate-binder ratio on the Thermal Coefficient of an Epoxy System. Source: Reference [6]

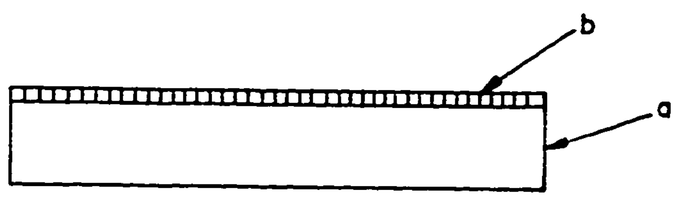


Fig. 1.4a: A Layer of Epoxy (b) Adhered to a Thickness of Concrete (a).

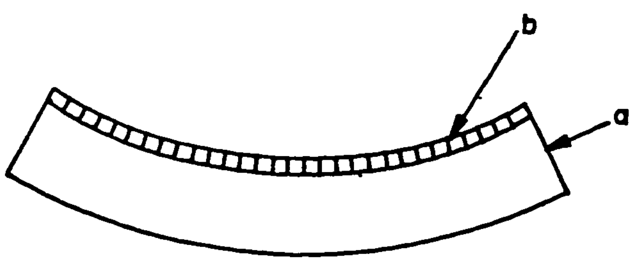


Fig. 1.4b: The Effect of Temperature Increase in an Epoxy-Concrete System.

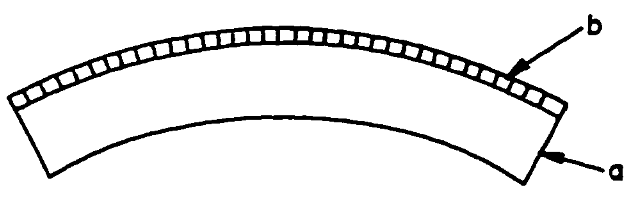


Fig. 1.4c: The Effect of Temperature Decrease in an Epoxy-Concrete System.

exotherm, or heat of reaction, during their cure. The temperature rise depends on the mass and formulation of the epoxy. In order to reduce this temperature, it is preferable to keep a larger surface area to volume ratio during mixing and application, and to add the maximum amount of aggregate consistent with the intended application.

x) Curing and Aging Stresses: Curing and aging stresses are developed in epoxies. However, they can be minimized by correct formulation to have stress relieving characteristics.

xi) Thermosetting Properties: Epoxy resins are thermosetting plastics, i.e. they undergo chemical change during hardening and cannot be reliquified by heating.

1.3.4 Uses of Epoxy Resins

Epoxy resins have found a wide variety of applications with concrete. Yet, an epoxy system composed of a resin and a hardener cannot satisfy all the conditions of different applications, and it has to be tailored in order to meet the end use requirements. Formulators specialized in epoxy resin industry can change the properties of these epoxies by the addition of diluents, fillers, flexibilizers, etc. to produce systems for specified applications. Therefore, it is important to adhere to the formulator's recommendations for use [6].

The main uses of epoxy resins with concrete are as follows:

i) <u>Protective Coating</u>: Epoxies are widely used as protective coatings for concrete because of their good impermeability to water and their good resistance to attack by most acids, alkalis and solvents. The thickness of such coating ranges from 0.05 or 0.8 mm (2 or 3 mil) to high-build coatings amounting to overlays. An essential property for epoxy when used as coating with concrete is to avoid or relieve extensive shrinkage and thermal stresses in order to avoid delamination caused by loss of bond or failure of the concrete. Coating highway or bridge deck surfaces with epoxy to prevent the ingress of water and deicing solutions into concrete is one example for this application.

ii) <u>Decorative Coating</u>: Epoxy resins serve exceptionally well as tile-like coatings; however, they surface chalk in outdoor exposure and their high cost in comparison to other types of paints generally limit their use for this purpose to special situations. Epoxies are particularly suitable for floors, car washing areas, and outdoor locations such as patios and porches, because of their good resistance to water and wear.

iii) <u>Skid Resistance Coating</u>: Concrete can be made highly skid resistant by the application of an epoxy coating in which mineral particles are imbeded. Typical applications are treads of stairways and walkways, and highway pavement surfaces.

iv) Grouts and Crack Fillers: Epoxy materials are widely used as grouting materials. Filling cracks is one of the more frequent applications, either to seal them from the entrance of moisture and other harmful materials or to restore the structural integrity of the member. Cracks upto 6mm ¼ (in.) are most effectively filled with pourable or pumpable epoxy compound, while epoxy resin mortar should be used in the case of wider cracks. Epoxies are used for grouting metal dowels, bolts, and posts into the concrete, and also as grouts for setting machine base plates, foundation alignment, etc. Chemical anchors are increasingly being used over the more conventional mechanical anchors as they offer excellent bond and do not stress the structure.

v) Adhesive: Epoxy resins are good adhesives for almost all materials used in construction such as concrete, masonry units, wood, glass, and metals. However, it cannot bond effectively to some plastics such as polyethylene. Typical applications in which epoxy resins are used to join various materials to hardened concrete include the joining of masonry units, precast concrete bridge deck girders, wood and metal signs, and plastic traffic marker signs.

Epoxies are also used as a bonding medium between fresh concrete and hardened concrete as in the case of forming an overlay on an existing concrete slab. Epoxy used should be properly formulated to cure and bond properly under moist conditions of the fresh concrete layer. Similarly, they can be used as shear connectors for composite construction such as a metal beam and cast-in-place concrete slab.

vi) Binder for Epoxy Mortar and Concrete: Epoxy can be used as the sole binding material to form a resin mortar or concrete. These mixtures are used in patching or repair of surface defects in concrete structures, particularly highway bridges and pavements. Epoxy mortar and concrete can also be adopted to repair of hydraulic structures, where the continued submersion lessens the problem of thermal expansion.

vii) Underwater Application: Epoxy resin formulations can now be used to patch or grout concrete and other construction materials under either fresh or salty waters.

1.3.5 Important Considerations

For an optimum repair by epoxy resins it is important to select the most proper type which satisfies the field conditions and environment during and after the application. Following the manufacturer's instructions supplied with the epoxy materials is important to have best results. Tests for checking the surface preparation and the adhesion of epoxy compared to concrete are strongly recommended [6].

The American Society for Testing and Materials (ASTM) provides a standard specification for epoxy-resin-base bonding systems for concrete (ASTM-C881) [15]. It includes a group of tests to be applied on these materials, and it classifies them according to their function, flow characteristics, range of temperature for which they are suitable, and color. It classifies the bonding systems into three types:

a) Type I: for use in bonding hardened concrete and other materials.

b) Type II: for use in bonding freshly mixed concrete to hardened concrete.

c) Type III: for use in bonding skid resistant materials to hardened concrete, and as a binder in epoxy mortars or epoxy concretes.

ASTM classifies epoxies into three grades with respect to their viscosity; grade 1 of low viscosity, grade 2 of medium viscosity, and grade 3 of non-sagging consistency. Three classes of epoxy systems are available: Class A, for use below 4.5°C (40°F), Class B, for use between 4.5 and 15.5°C (40 and 60°F) and Class C, for use above 15.5°C (60°F). Epoxy resins are normally unpigmented, but they can be colored or darkened. This standard specification provides a table for the physical requirements of the bonding systems of the three types based on this classification and the tests required to perform it.

Some suppliers use ASTM-C881 in order to classify their products, others mention in the manufacturer data sheet the physical properties of the product that are important to the purchaser. The ASTM standard can also be used by the purchasers in order to select the proper epoxy bonding system and to test it accordingly, thus assuring that it satisfies its required physical properties.

British standards have also developed a standard specification for testing of resin compositions for use in construction (BS 6319) [21]. The standard provides a collection of test methods for testing the performance of resin based compositions as used in the construction industry. This standard can also be used for research purposes (e.g. assessing performance under various conditions, or for comparison between resin compositions from different sources).

The bond between epoxy and concrete depends very much on the surface of concrete, and therefore, it has to be well prepared , being free from any loose materials and any contaminants such as grease, oil, dust, stains, etc. The surface should be completely cleaned and also it should be dry before and during cure, otherwise, a proper epoxy formulation which is suitable for damp concrete is to be used. Generally, field tests [6] are available and considered as necessary for checking the condition of the surface of concrete to receive epoxy resin as well as the addition of the epoxy resin compound [6].

A chemical reaction undergoes between epoxy resin and their hardeners or curing agents upon the hardening process. Therefore, the two components should be mixed with the specified ratio mentioned by the manufacturer and be mixed thoroughly in order to have homogeneity of the epoxy compound and complete reaction between its components. An accuracy of the specified epoxy resin to hardener ratio varies with each epoxy compound. In most cases an accuracy of plus or minus 5 percent is acceptable, although an accuracy of plus or minus 2 percent is highly desirable. Some epoxy compounds can tolerate a wider variation but test data should be available reflecting the effect of this variation on the physical and chemical properties of the epoxy compound. Temperature of the components can affect the mixing procedure considerably, and temperature conditioning, cooling or heating of the epoxy components may be required [6].

The applicator should be sure that the epoxy used has the rate of hardening and viscosity required by the specific job. Both properties are affected considerably by the temperature of the site at the time of application, and both affect the amount of thickness of the epoxy layer. The amount of sag and thickness achieved in the epoxy layer depends partly on whether it is applied on a vertical surface, on the top of a horizontal surface, or the bottom of it, and whether the surface is flat or irregular. Highly absorptive concrete or concrete made of absorptive aggregates may absorb enough epoxy to make the layer at the bond line insufficient, and a second coating of epoxy layer is needed then. However, the second coating should be applied while the first coating is still tacky, and if the first coat hardened, the surface would require second blasting in order to bond to the next coating. Intimate contact is necessary for effectiveness and all necessary measures should be taken to assure complete wetting. Thorough wetting may be more difficult to obtain with epoxy resin mortar or concrete than with a plain binder. Temperature conditioning of the surface of the substrate may be needed since temperature affects the rate of hardening effectively. The job can be opened to service after enough strength has been obtained. In many cases it is difficult to reach the surface of cured epoxy for strength evaluation and then it is advisable to depend on the supervisor's experience and the manufacturer's data on the anticipated strength with respect to time [6].

Equipments used in the repair process by epoxy resins, if not disposable, should be cleaned from epoxy compounds before cure. That is achieved by immersing the tools used in a solvent, where complete cleaning and drying is necessary before reusing the tools. There are methods which can remove epoxy resins if they have cured such as immersing tools and containers contaminated with cured epoxy in strippers for a long period of time (at least overnight), where these liquid compounds will attack the cured epoxy, abrading the cured epoxy mechanically using a grinder, and burning of metal tools and containers using temperatures of about 260°C (500°F), when they will not be damaged by such high temperatures and where ventilation is provided to avoid inhaling vapors released from the combustion of such epoxy resins. An alternative way for maintaining the equipment is to prevent the bond between epoxy and tools and containers from the beginning by applying release agents such as silicone sprays, spray-on films and special wax emulsions, where excessive abrasion is not encountered, and when it is assured that these release materials will not contaminate the epoxy compound or interfere with the proper cure or bond [6].

There are certain handling precautions that have to be taken when dealing with epoxy resins. Epoxy materials vary in degree of hazardness between non-hazardous materials and extremely hazardous ones when improperly handled. They may cause health problems when carelessly handled such as skin irritation and skin sensitization. Working in a well ventilated area, wearing eye-glasses and disposable suits and gloves, and following the manufacturer's instructions related to safe handling of the materials should be taken for a safe repair process. Careful attention is to be given when dealing with solvents also since some of them are flammable, producing toxic vapors, or causing burns or other serious effects. If it happened that epoxy compounds came into contact with the skin, they should be removed by water and soap immediately. It is generally true that solvents should not be used to remove epoxy materials from the skin because they will tend to dry the skin and may cause skin dermatitis by themselves. Additionally, they dissolve the epoxy and carry it into more intimate contact with the skin thus increasing the dermatitic problem resulting from the epoxy compounds. Flushing eyes with large amounts of water and seeking an immediate medical attention is necessary if eyes come into contact with such chemicals [6].

1.4 Repair of Cracks by Epoxy Injection

Cracking of concrete may result from normal service loads, internal stresses, or overloading of the structure [5].

Reinforced concrete members are normally designed in a way that most of the tensile strength of steel is utilized for best efficiency and economics. Therefore, steel usually undergoes some elongations which may exceed the breaking strength of concrete under normal service loads, and that results in hairline cracks in concrete, invisible to the naked eye. The cracks are bound to occur even for properly dimensioned members when subjected to tension or flexure. However, these cracks are harmless, provided that steel is designed and configured properly so that no wide open cracks are developed and enough cover is available. Under normal conditions these hairline cracks will not increase the risk of reinforcement corrosion or impair the stability or serviceability of the structure [5].

The shrinkage of concrete both in the plastic and hardened states, as well as temperature variation will lead to internal movements of concrete members. If these movements are restricted as in the case of statically indeterminate structures, tensile stresses will develop and may lead to cracking. Similar internal stresses will occur as a result of fire or differential foundation settlements. These are the most common causes of cracking. While cracks resulting from shrinkage, fire or settlement, usually stabilize after the cause is removed, those cracks caused by temperature variations may continue to move under certain conditions such as repetitive ones. This is an important factor in selecting the proper repair system. In case of doubt, plaster seals may be applied over the crack to observe any further movement.

In the case of cracking as a result of overloading, it is important to distinguish between loads which are applied as a single occurance (accidents, disasters), and those which are applied continuously to the member during its service life [5].

It is normally difficult to assess the effect of cracking on the serviceability of a structure. Origins and causes must be considered. The first judgement to be made is whether the stability of the structure or a structural member is threatened. This is seldom the case, but if there is a doubt, structural engineering advice should be sought. If there is no immediate risk to the stability of the structure, its service life may be shortened due to the migration of water, air, and other harmful substances into the inside of concrete causing corrosion of reinforcement and other harmful effects if these cracks were wide enough. Cracks less than 0.2mm (0.008 in.) are considered to pose no threat of corrosion under normal service conditions. In aggressive environments this limit goes down to 0.1mm (0.004 in.) Finally, cracking may affect the serviceability of concrete structures designed to retain or exclude liquids, such as water tanks and reservoirs. These structures may be at risk even if the width of the cracks is within the above specified limits [5].

Basically cracks which results from one-off application of stress and have already ceased to move can be sealed by injection of special epoxy resins, thereby restoring the structural integrity of the member and removing any threat to its durability or serviceability. If it is just a matter of protecting steel reinforcement from corrosion, as in the case of cracking in the tensile zone of concrete, it may suffice to seal over the crack by brushing on several coats of a suitable resin compound [5]. Alternatively, when narrow cracks have only to be sealed against moisture, it is sometimes sufficient to brush dry cement or neat cement grout into it. Another method is to seal them with latex - emulsion of low viscosity. Wider cracks can be filled with latex-cement mixture to which a "thickener" may be added to promote gelling and help to retain the filling material inside the crack. These materials have relatively low elastic moduli and do not generally contribute to the strength of the structure [4]. Injection treatment may also be effective in certain cases, where cracks are still subject to movement, whether as a result of temperature fluctuations or changes in service/traffic loads, i.e., if it is simply a matter of protection of steel reinforcement against corrosion, and if the width of any further crack is within the above mentioned limits [5].

In all other cases cracks may necessitate structural repairs or it may be considered as expansion joints and sealed accordingly. If cracking is due to lack of structural strength of the member, then the only satisfactory solution is to bond entire reinforcement to outside of the member using special adhesives, or to provide some form of additional concrete support. If the structural strength of the member is not impaired and further movement is expected, the crack can be sealed along its sides by a special flexible cover strip; alternatively, the sides of the crack can be opened to form a proper chase and the crack can be considered as a normal construction/expansion joint and filled with a suitable joint sealent [5]. Forming a chase will make the seal considerably wider than the crack in order to reduce the strain to a reasonable amount. Then it can be sealed with an elastic material such as polysulphide rubber or a preformed neoprene or rubber-bitumen sealing strip, or a flexible 'bandage' can be applied to the surface of the member (Fig. 1.5). It is preferable to seal the crack at its most widest so that the sealent has not the tendency to be pulled away from the concrete by the subsequent movement. The sealent should not bond to the bottom of the chase in order to be subjected to direct stress only, but it is important to ensure that it is fully bonded to the sides of the chase. When a surface seal is applied, the bandage should be stuck to the concrete at its edges while the central part is free to move as in Fig. 1.5. When only very slight movement is expected, it may be possible to use a 'high build' surface coating, such as coal-tar/polyurethene, in several coats [4].

If signs of corrosion of the underlying reinforcement showed up, alternative methods of repair are required in this case [5].

ACI 504-70 describes practices for grouting and sealing cracks and joints, including joint design, material available, and methods of application. The basic steps in the process of filling a cracks are as follows [6]:

1) Sealing the Surface: The first step is injecting a liquid epoxy resin into a crack after cleaning and preparing it is to cover all the surfaces of the crack with a surface seal to prevent leakage and flow of the liquid resin out of the crack before gelling and curing. There are two methods for applying this seal:

a) Routing: frequently the crack is V-grooved or routed

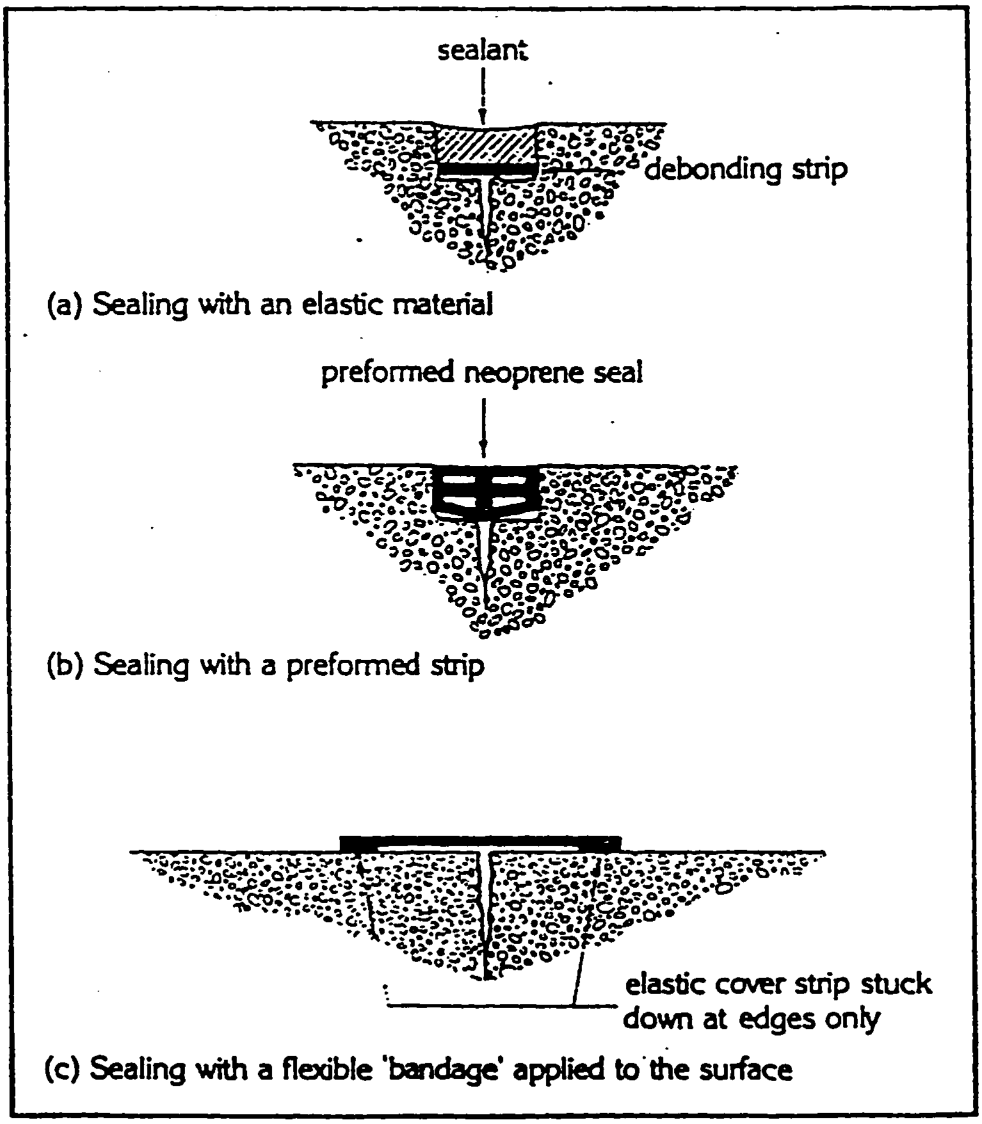


Fig. 1.5: **Methods of Sealing a Crack When Further Movement is Expected. Source: Reference [4]**

to a depth of about 13 mm (½ in.) and a width of approximately 19 mm (¾ in.) using light chipping hammers or a grinding tool. The V-grooved crack is then filled with a non-sagging epoxy adhesive compound or mortar which is applied like putty and then struck off flush with the concrete surface. This type of sealing is used most frequently with very high pressure crack injections.

b) Surface-dam: an alternate method for sealing or damming the surface of the crack is to apply a seal merely to the face of the crack and completely bridge it. The material used is frequently a non-sagging epoxy adhesive also, which sets rapidly. In some cases a thermoplastic seal is used, where it is applied at an elevated temperature [6]. Many of the materials used for sealing the crack between injection can be peeled off on completion of the work without disfiguring the concrete [4].

Injecting the adhesive into the crack requires entry ports at the injection points, and there are three types of them in use:

i) Drilled holes-fitting: the method which was historically first found and is used always in conjunction with V-grooved cracks is to drill a hole into the crack of almost 19 mm (¾ in.) in diameter and

13 mm (½ in.) to 25 mm (1 in.) below the apex of the V-groove and bond into it a fitting such as pipe nipple or tire-valve stem with an epoxy adhesive. The fittings are bonded with the same epoxy adhesive, which was used to fill the V-groove portion of the crack [6]. Care must be taken to prevent dust, resulting from drilling, from blocking the crack and hindering the flow of resin. The use of a drill bit with a suction attachment is one way to do so [4].

ii) Bonded Flush Fitting: when the crack is not V-grooved, a method which is frequently used to provide an entry port is to bond a fitting flush to the concrete face over the crack. This flush fitting has a hat-like cross section with an opening at the top for the adhesive to enter.

iii) Interruption in seal: a portion of the crack can be used for injecting the resin when it is not sealed. This type of system can be used with special gasket devices, which will prevent leakage while injecting the resin into the crack.

2) <u>Mixing the Adhesive</u>: This is done by either the batch or discontinuous method. In the batch method the components of the epoxy compound are mixed together with the propor-

tions given by the manufacturer, usually by a mechanical stirrer such as the paint mixing paddle. Care must be taken not to mix more material than the amount that can be injected, before it starts to gel. The flow characteristics of the epoxy compound change when it begins to gel, and that makes the injection process more difficult. In the continuous system the two components pass in separate hoses through metering and driving pumps, prior to passing through an automatic mixing head. This system allows the use of fast-setting adhesives that have a short working life in a larger mass, and also it enables the injection of cracks, where access of the work is difficult without a long hose.

3) Pumping the Adhesive: The adhesive is injected into the crack by an injection system such as the following ones:

a) Pressure Pot: perhaps the most frequently used method is to force the adhesive with air pressure from a standard paint pressure pot through hoses to the entry port. The adhesive may be placed in a disposable container within the paint pot.

b) Caulking gun, air or head actuated: A common method also is to fill a caulking gun cartridge with mixed adhesive and apply pressure.

c) Hydraulic Pump: The adhesive is driven through hydraulic pumps which receive liquids from reservoirs. The adhesive material can be either gravity-fed or force-fed to the driving pumps.

The adhesive is injected into the crack through successive adjacent ports. Care must be taken not to apply a high pressure which the surface seal cannot tolerate or which can damage the structure, or which may make the resin take the path of least resistance close to the surface instead of penetrating deeply into the crack.

In horizontal members such as a floor the injection of epoxy proceeds from one end of the member to the other and if possible from the bottom of the concrete member upwards. Cracks in vertical concrete elements should be filled starting from the lower part and proceeding to next part until the uppermost part is filled with epoxy taking care not to trap air pockets.

4) Making sure the Crack is Full: It is very difficult during the injection process to be sure that the crack is completely filled and therefore personal experience of the applicator is very important. Some work has been done on sophisticated methods such as ultrasonic testing to determine whether the crack has been filled or not. One practical method of detecting filling of the crack is by drilling cores. It is absolutely necessary if the soundness of concrete has to be

assured. Some of the points in the repair process which can lead to a high degree of success are mentioned below:

i) Order of Injection: The adhesive should be injected through successive ports starting from the lowest one. Injection should continue from one port until it starts to come out from the next. Then first port should be capped off and injection starts from the port which has just begun to show the adhesive.

ii) location of Port: Entry ports should be spaced far enough to assure that when the adhesive has come out of the next port, it has completely filled the crack to its full depth. Normally they are placed only as far apart as the depth of penetration desired.

iii) Calculation of Theoretical Amount Required: A useful technique which helps to ensure filling of the crack is to estimate the theoretical void by measuring the width of the crack and dimensions of the concrete member. Injection proceeds until the estimated quantity is fed with a factor of safety (1.5:1 has proved suitable). If the theoretical amount cannot be injected, the cause should be determined. Possibility of any undetected voids of undetermined size connecting with a crack must be recognized and the amount required for filling them determined and limited.

iv) Maintaining Pressure: If pumping pressure cannot be maintained in a crack that is otherwise apparently full, the reason should be determined. Inability of maintaining pressure could be due to leaking out through the surface seal or vent hole, draining into connecting cracks, or passing through the member into voids on the other side.

5) Removing the Surface Seal: After the injected adhesive has cured the surface seal should be removed by grinding or whatever methods are necessary. Fittings and holes at entry ports should be painted with an epoxy patching compound.

Ideally, the adhesive should be compounded for pressure injection into concrete cracks. Therefore, it should be pumpable, readily assimilated in small cracks by capillary action and capable of bonding through a layer of dust and fines that might be available inside the crack. Cracks which have been contaminated with oils, grease, food particles, and chemicals present special problems, and unless they are removed sufficiently by proper methods to allow for adhesive penetration and pressure bond, grouting will not be an effective repair procedure. Dirt or fine particles prevent penetration of the adhesive. They should be removed by flushing out with water, followed by drying or blowing them out using compressed air [6]. If the surfaces of the crack are moist, a resin should be chosen that will adhere to damp surfaces. This is usually more effective than trying to dry the crack by flushing out with a water repellent material [4].

Chapter 2

LITERATURE REVIEW AND ROLE OF THE STUDY

2.1 Literature Review

2.1.1 The Problem

The rapid growth in the construction activity in the Arabian Gulf area for the past two decades has intensified the demand for reinforced concrete and concrete block as the most popular form of construction. There has been an unprecedented demand for concrete buildings of all kinds and the construction industry, beset by an inadequate infrastructure, shortages of suitable materials, equipment, skilled manpower, and inadequate specifications and construction practices, has succeeded only in producing structures which are showing an alarming degree of deterioration within a short span of 10-15 years. The deterioration is accentuated by the geomorphic and climatic environmental conditions which are characterized by reactive and marginal aggregates, high temperature-humidity environments, and severe ground and ambient salinity [1].

In the following sections some aspects of the severe environment of the region are mentioned, followed by a brief history on the development of epoxy materials for use in the construction industry, and then a review on the research related to the application of these materials in the field of construction is presented.

2.1.2 Severity of the Regional Environment

The Arabian peninsula has an arid [(precipitation 5 cm/year (2in/year), evaporation 124cm/year (50in/year)] sub-tropical climate in terms of global climatic classification. The coastal flats, where much of the development is founded, are exposed to saline oceanic influences and the environment is characterized by intense heat often associated with high humidities and strong persistent drying winds. The coastal areas along the southern part of the Red Sea have the highest annual mean temperature in the world. Summer air temperature in coastal areas and especially in the central part of the Arabian peninsula frequently attain 45-50°C (113-122°F). The humidity in the coastal areas is very frequently around 60% touching 100% at times. The annual rainfall is almost always less than 127mm (5 in) Isohyet, a figure often used to define the zone of greatest aridity. Extremely low precipitations (less than 5 cm/year = 2 in/year) result in salt accumulation on surface, and the combined effect of frequent drying winds, high temperatures, and low precipitation results in excessive evaporation of the Gulf waters (124 cm/year = 50 in/year) causing high salinity, especially in coastal areas [1]. Fig. 2.1 shows these climatic characteristics as well as the detailed month-by-month variations of temperature, humidity and precipitation for a typical location in Eastern Saudi Arabia [1]. It is also of interest to mention that concrete exposed to direct sun rays may

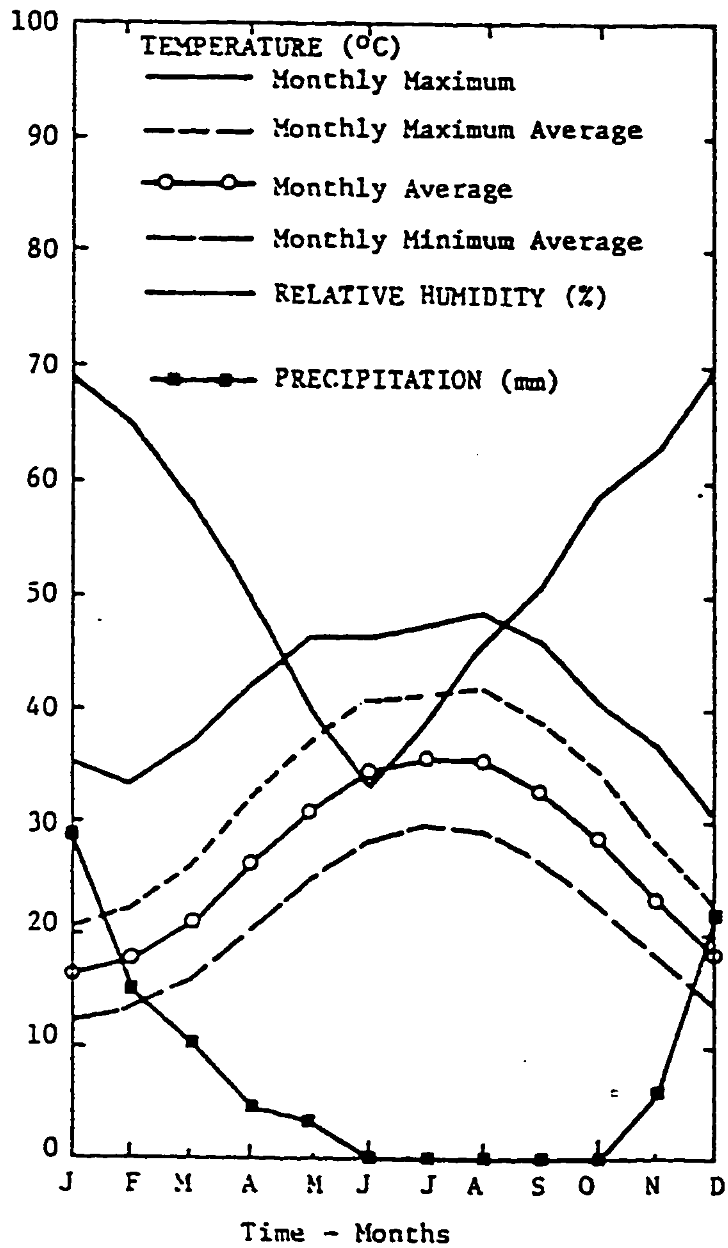


Fig. 2.1: Climatic Data for Dhahran, Saudi Arabia
Source: Reference [1]

reach temperatures as much as 30°C (86°F) higher than the ambient [2].

Considerable studies and corrective measures are being taken in the concrete construction industry in this area as a result of this alarming situation, and different techniques of repair work are being implemented to restore some of the deteriorated structures.

2.1.3 History of Epoxies

The first practical application of epoxy resins took place in Germany and Switzerland in the 1930's with concurrent experiments being conducted in the United States, although the basic chemistry had been known for several decades. Limited production of epoxy resins started in the late 1940's and commercially produced epoxy resin adhesives became available in the early 1950's. Initial laboratory tests using epoxies on concrete started also in the late 1940's and were directed towards using them as coatings on floors and highways. Developments were limited to the laboratory until 1953, as engineers and scientists attempted to identify the basic physical properties and probe potential uses of epoxy systems. Epoxy formulations developed until there were epoxy systems with a combination of properties which made them uniquely suited to be used as an adhesive with concrete. They have high bond strength, low shrinkage during cure, characteristics similar to other structural materials when cured, long term resistance to aggressive environments, and easy application characteristics. Those properties led to many different applications. Epoxies are presently used with concrete in the form of coatings, repair materials, grouts, bonding agents, paints, adhesives, epoxy mortar and concretes, seal coats and wearing surfaces. The volume of applied epoxies has been increasing and their costs have accordingly decreased [6].

2.1.4 Literature in the Field of Epoxies

There is a vast amount of literature in the field of using epoxy resins with concrete, varying from highly academic articles (e.g. [9]) to very practical ones (e.g. [10]). The literature related to this field can be divided into three major categories, namely; (1) literature related to developments of epoxy resin systems and their different applications, (2) literature related to the development of testing techniques for the evaluation and comparison of the performance of different epoxies for research as well as practical applicaitons, and (3) literature related to the performance characteristics and durability of epoxy products under various environmental conditions.

These categories are mentioned in more details below with more emphasis on the literature related to this thesis subject:

(1) Literature related to developments of epoxy resin systems and their applications:

There is a large number of articles which deal with the repair of structures using epoxy compounds. For example, reference [6] is an ACI Committee 503 report entitled "Use of Epoxy Compounds with Concrete" and it provides a complete review for the history, properties, and uses of epoxy compounds with concrete as well as the details of the different steps undertaken in the repair process. Reference [11] summarizes the crack repair methods and tells what kind of cracks can be repaired with each of the mentioned methods. It is a condensed form of the ACI Committee report entitled "Causes, Evaluation, and Repair of Cracks in Concrete Structures". Concrete repair and protection, starting with mentioning the different causes of concrete deterioration and ending with some examples of case histories together with a collection of products that can be used in this field, are provided in reference [5]

Some literature concerns about the new developments in epoxy formulations and applications, and the behavior of these epoxies inside cracks. Plecnik et al [12] studied the effect of viscosity, pot life, and injection pressure of epoxy adhesives on their penetration capability as the latter is largely responsible for an effective repair and rebonding of steel reinforcement. Tests have been executed on epoxy injections in concrete bridges in reference [9]. It discussed the interdependence of some intrinsic properties in the liquid state as reactivity and viscosity in one hand and workability and viscosity on the other hand. It mentioned that further work has to be done on systems suitable to react properly in wet environment and on the question of crack opening displacement in the hardening state of the resin.

Research in this category also includes the new techniques developed in applying these adhesive materials and in trying to use them to repair various forms of deterioration. Reference [13] is a report published by Kansas Department of Transportation on a project in which a technique was developed for repairing cracked structural bridge concrete. The method developed consists of drilling holes at an angle to the deck surface, filling the hole and crack plane with epoxy pumped under low pressure, and placing the rebar into the drilled hole in a position to span the crack. Blight et al. [14] have experimented with the use of epoxy resin injection repair scheme in structures affected by alkali-aggregate reaction. They reported limited success.

(2) *Literature related to the development of testing techniques for the evaluation and comparison of the performance of different epoxies for research as well as practical applications:*

Methods for evaluating and comparing the different epoxy adhesives are actually very necessary. They help producers to provide, as well as users to select, the most proper product to be used in the field prevailing conditions. These test methods are helpful also in research purposes related to these materials. Evaluation and checking the characteristics of epoxy materials are very important. Also, the availability of a wide range of epoxy adhesives in the local market makes the comparison of their properties under local conditions very beneficial. Although they come late, there are some standard specifications which help to achieve these goals. Some producing companies developed their own test methods on which they depend in evaluating the properties of their products. Many researchers are working in developing the different test methods and techniques and it seems more work and standardization is required.

Most of the reported experimental work has centered around beam type members, with initial failure initiated in tension and in shear. Most of the researchers initially damage the members through overloading, and then proceed to repair the cracks [at least those by resin injection, and study the stiffness related parameters (e.g. load-deflection, load-crack width, recovery of deflection, and ultimate load characteristics) of these repaired beams in comparison with the original damage-free beams. References [28-32] are a representative collection of such testing, with loads applied either in a static or dynamic fashion under normal environmental conditions.

On the other hand, the American Society for Testing and Materials (ASTM) provides a standard specification (C881-78, reapproved 1983), for Epoxy Resin Base Bonding Systems for concrete. This specification covers two-component epoxy-resion bonding systems for application to portland cement concrete. It classifies epoxy-resin bonding systems by type, grade, class, and color according to the type of function and use, flow characteristics, range of temperature for which they are suitable and color, respectively. The specification provides useful information for both producers and users and it describes the test methods used to determine the important characteristics of epoxy-resin bonding systems. Finally, it ends with a table showing the physical requirements of bonding systems regarding viscosity, consistency, gel time, bond strength, volatile content, absorption, shrinkage, and thermal compatibility. ASTM (C882-C884) provide standard test methods for bond strength, effective shrinkage of epoxy-resin systems used with concrete, and thermal compatibility between concrete and an epoxy-resin overlay, respectively [15-18].

In the standard test (ASTM C882-78, reapproved 1983) for testing the bond strength of epoxy-resin systems used with concrete, the bond strength is determined by using the epoxy system to bond together two equal sections of a cylinder made with portland cement mortar, each section of which has a diagonally cast bonding area at a 30^{0} angle from vertical (Fig. 2.2). After suitable curing of the bonding agent, the test is performed by determining the compressive strength of the composite cylinder [16].

ACI 503.4-79, is an American Concrete Institute standard entitled "Standard Specification for Repairing Concrete with Epoxy Mortars", and it describes the work of repairing defects in hardened cement concrete with a sand-filled mortar using an adhesive binder such as defined in ASTM C881. It includes controls for adhesive labeling, storage, handling, mixing and application, surface evaluation preparation, as well as inspection and quality control [20].

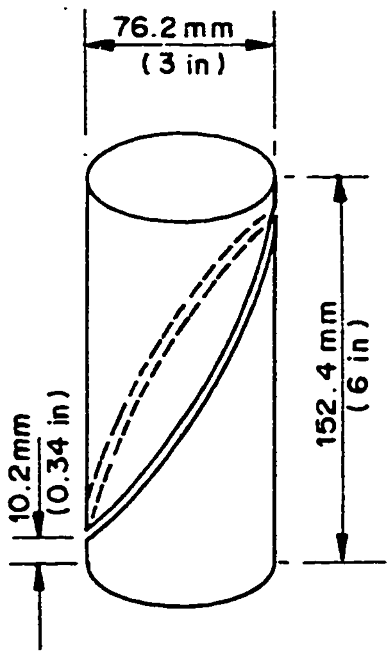
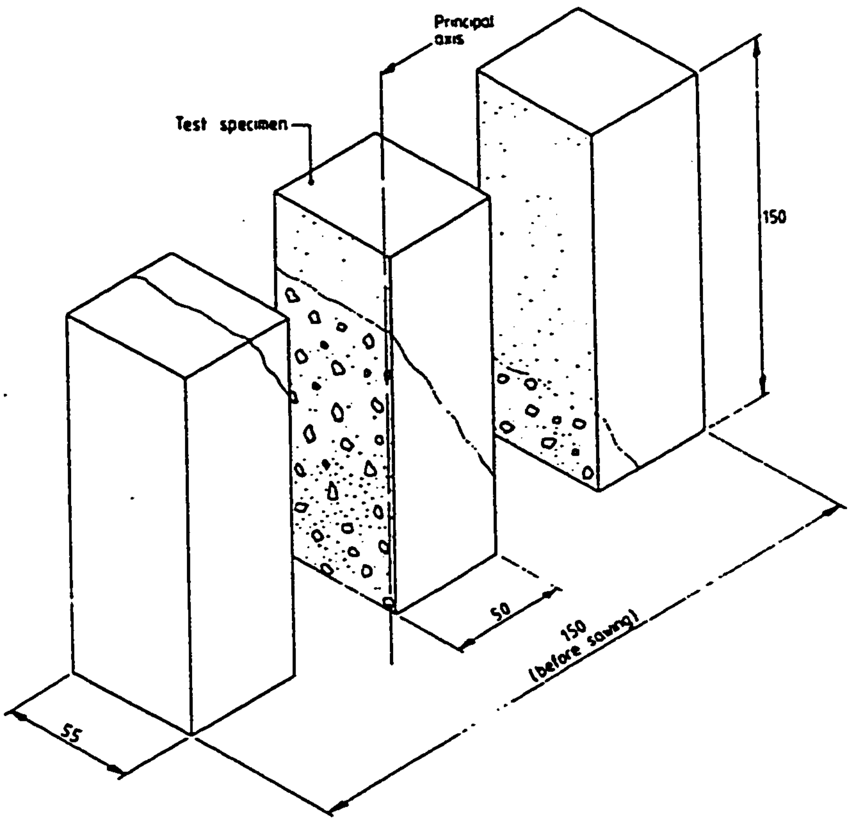


Fig. 2.2: A Cylindrical Specimen for the Slant Shear Test Described in ASTM C882-78 [16]

The British Standard Institution (BSI) has provided a British Standard (BS 6319:1983) under the title "Testing of resin compositions for use in construction". The parts of this standard provide a rationalized collection of methods for testing the performance of resin based compositions as used in the construction industry. The methods described in this standard allow for the tests to be carried out either under specified conditions or under agreed and declared conditions so allowing the freedom necessary for research purposes (e.g. assessing performance under various conditions) or for checking maintenance of quality. If the purpose of the tests is to prepare general data for facilitating comparison between resin compositions from different sources, then it is strongly recommended that the more specified ambient conditions described are adopted [21].

Part 4 of this standard (BS 6319:Part4:1984) includes a method for the measurement of bond strength (slant shear method). This test method is a further development of the earlier methods, and has overcome some earlier deficiencies. It allows better simulation of constructions in which resin compositions are used. Of particular importance is that it can be successfully used to evaluate crack repair materials and techniques. Thus it shows how the slant shear test is the most proper test for evaluating bond strength between the adhesive and hydraulic cement concrete. If the bond is loaded in compression, little information will be obtained since direct compression failure is more likely to occur in one or other material. Prior failure of the bond line could be due to an indirect effect resulting from shear stresses due to differences in the elastic responses of the two materials. Tension tests lead to tensile failure in hydraulic cement concrete in most cases, a mode this material is known to be weak. Hence 'pull-off' tests seem to be of little value since they measure the tensile strength of concrete, not of the bond. When hydraulic cement concrete members are required to accommodate a tensile force, this is achieved by the introduction of tensile reinforcement, most commonly steel. The high tensile strength of reinforcement is mobilized by means of bond and shear stresses in the concrete. Shear stresses are also generated as a result of elastic response when concrete is loaded in compression. Thus it would appear that the shear properties of the adhesive are the most worthy of investigation if its useful strength is required. In order to subject the bond line between hydraulic cement concrete and a resin composition to a pure shear stress, an elaborate set-up is required if turning moments and tensile stresses are to be avoided. A similar approach is to apply a compressive load to a specimen taking the form of a composite prism with a bond line running diagonally through it where the bond line will be subjected to a combination of shear and compressive stresses, a condition most likely to be encountered in concrete structures. This method of investigation of the strength of an adhesive bond is known as diagonal or slant shear bond test. The ratio of shear to compressive stresses increases as the angle between the bond line and the vertical axis is reduced. It has been found that 30^0 angle is



Dimensions are in millimetres.

Fig. 2.3a: Plaque Sawn to Produce Test Prism

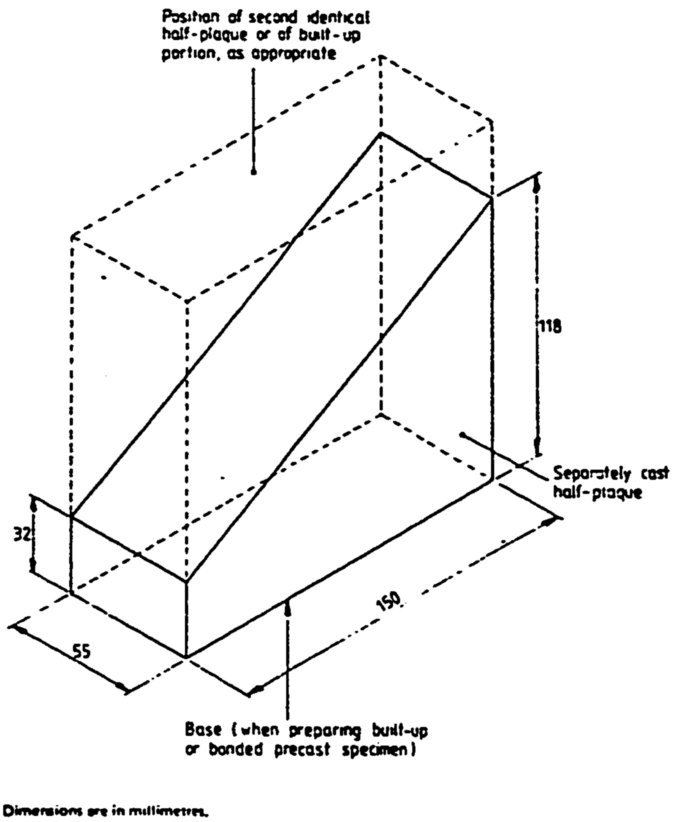


Fig. 2.3b: Dimensions of Cast Half-Plaque Used for Preparation of Built-Up or Bonded Test Specimens.

Fig. 2.3: Specimens for the Slant Shear Bond Test as Provided in BS 6319-Part 4 [21] Source: Reference [21]

the shallowest practicable angle at which a joint can be formed in a prism of modest dimensions. The slant shear test may be used not only to appraise the bond strength of materials but also to consider the effect of concrete pre-treatments (e.g. acid etching) upon the bond strength. Appendices at the end of Part 4 describe the preparation of composite test plaques representing the more typical constructions in which resin compositions are used (Fig. 2.3). The principle of the test may be adopted for other composite constructions, provided that full details are given in the test report. Similarly the test can be applied to damp portland cement concrete or be applied underwater, to investigate the effect of environmental conditions on the bond strength [21].

Ciba Giegy [22] presented guidelines for testing araldite epoxy resin-based structural adhesives and mortars. They serve primarily to determine the behavior of adhesives and highly filled mortars when subjected to short-term and long-term stresses, and when exposed to moisture and heat. Unfilled binders, e.g. such as injection systems, are tested in accordance with the general standards applicable to plastic materials. It also uses a similar slant shear test for testing the mechanical short-term and long-term performance of epoxy resin adhesives under combined shear and compressive strengths and also when exposed to moisture and heat. It mentions that knowledge of the behavior of epoxy resin adhesives and mortars under thermal stress is of considerable importance when selecting these products for use in structural applications. Accordingly it is absolutely essential to determine the temperature limit below which an epoxy adhesive or mortar will perform satisfactorily over a prolonged period.

Fattuhi [23, 24, 25], suggested two simple techniques for testing the performance of different adhesive materials in transmitting tensile and flexural stresses across a crack as there is no standard available in this respect. The two techniques can also be used in checking their performance as well as for comparison purposes with respect to given parameters and conditions. In order to compare the behavior of different adhesives, the specimen geometry should be the same, and as it is difficult or nearly impossible to obtain fractured surfaces of the same geometry, a crack simulation technique during the concrete casting was adopted. The technique may result in lower loading strengths than those obtained by using fractured surfaces, where the interlocking nature of the adjacent crack surface produces higher resistance to failure. For the first technique [23, 24, 25], molds for flexural beams of dimensions 500 x 100 x 100 mm were used. A 100 x 50 mm steel plate was placed at the center of the mold so that a groove (simulated crack) was formed in the beam after casting the concrete, demolding and removing the steel plate. The dimensions of the steel plate were such that the resulting groove would extend through the tension zone of the beam during testing (Fig. 2.4). Preliminary investigations showed that the thickness of the plate, which represents the width of the beam crack, is critical

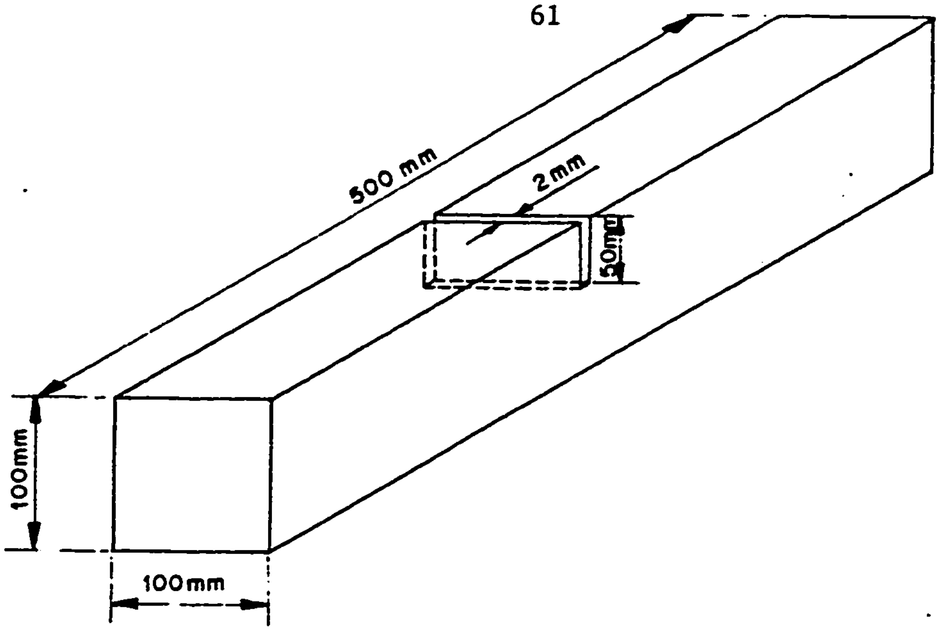


Fig. 2.4: Grooved Beam Specimen as Suggested by Fattuhi [23]

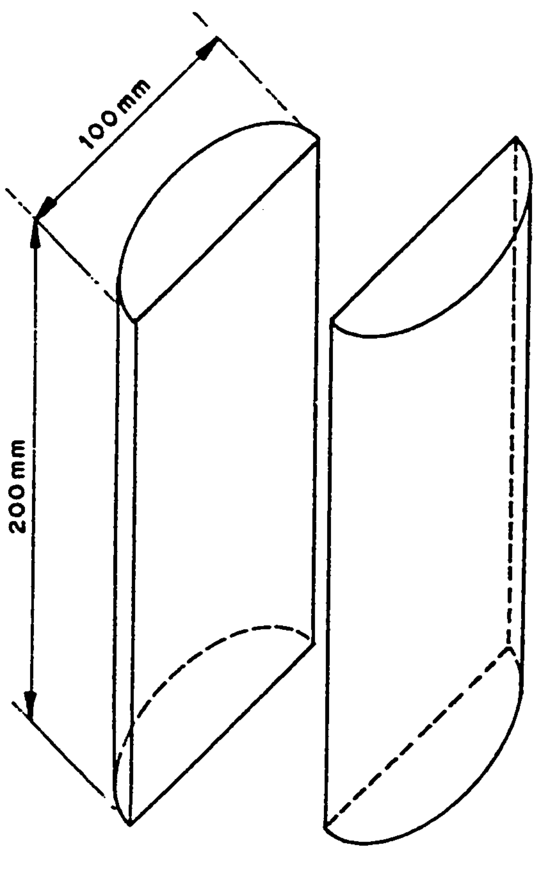


Fig. 2.5: Halved Longitudinal Concrete Cylinder as Suggested by Fattuhi [23]

when hand injection is used, since viscosity of the different repair materials varied considerably. Control specimens such as ungrooved and grooved unrepaired beams were also made, cured, and tested under similar conditions. It was recommended that these tests are carried out under equivalent conditions and compatible with actual field conditions, before a final choice of adhesive is made. For the second testing technique [23], halved longitudinal concrete cylinders were joined by repair materials and the cylinders together with complete unrepaired reference ones were tested under splitting tension (Fig. 2.5).

Amon and Snell [26], presented four case histories that showed how pulse velocity techniques could be used to monitor and evaluate epoxy grout repairs. The methodology of the evaluations and limitations of these procedures were discussed. This is a very important practical issue, as besides actual coring of a repaired structure, no other technique is known for evaluating the degree of penetration of a resin into a cracked structure. Reference [27] presented two statistical ways for assessing the efficiency of repairs by comparing ultrasonic pulse velocities before and after repairs on concrete and reinforced concrete structures. The methods were applied on bridge prestressed beams and the advantages of each were shown in examples.

A good review on test methods for assessments of concrete repair materials is available in reference [3]. Tests examined include physical, chemical and durability performance. Testing of whole systems was also considered both in simulated laboratory conditions and under natural exposure applied to purpose-made test specimens. Consideration was also given to the possibilities of testing the performance of concrete repair materials and systems in service. This review concentrated on the requirements of repair systems to overcome the effects of reinforcement corrosion in the structure. It showed that a repair system embraces a number of different components including bonding coats, patching material, and any surface coating. The performance requirements of each of these elements depend on its function and were determined, and then a comprehensive testing approach for these elements as well as the repair system as a whole was mentioned accordingly.

(3) *Literature related to the performance characteristics and durability of epoxy products under various environmental conditions:*

The performance of epoxy compounds used with concrete and their durability under various environmental conditions, or in other words, the short-term and long-term properties of epoxy materials, were of primary concern in the researches related to this field. Utilization of these materials in various areas of application depends mainly on these properties.

In reference [28] flexural tests on epoxy repaired beams showed that the repair process could enhance the structural performance of the defective concrete structures. In reference [29, 30] static and dynamic (impact) tests on push-off specimens showed the effectiveness of repairing concrete joints by epoxy injection. Hewlett and Morgan [31] studied the static and cyclic (reversed loading) response of reinforced concrete beams repaired by resin injection. Beams designed to fail both in tension and in shear were tested to failure, repaired, and re-tested. The work has established that if cracks are accessible to the resin (i.e. not less than 0.1 mm (0.004 in) wide), failed beams can be reinstated to a load-deflection and ultimate loads behavior at least as good as those of the unfailed beams. If the cracks are too narrow for resin penetration (less than 0.1 mm (0.004 in) inside), there will be no improvement to the beam's stiffness, but such cracks are not likely to affect the serviceability of the beam and would not require repair. If, however, bond between reinforcement and concrete has been destroyed or the reinforcement extended beyond its elastic limit, total reinstatement is doubtful. Extensive shear cracking could be reinstated and beams which had failed in this way were both stiffer and stronger than originally. Within the limits of that program, a resin within a crack had no deleterious effect upon the behavior of a repaired beam under reversed loading. Some of these results agreed with earlier investigations mentioned in that reference.

Hugenschmidt [33] presented some new experiences with epoxies for structural applications. In that paper the properties and testing of structural adhesives were reviewed in relation to such applications as segmental concrete bridge construction and the repair and strengthening of reinforced concrete structures. Criteria for the selection of epoxy adhesives were discussed with particular emphasis on creep deformation, heat stability, moisture resistance, on site conditions, handling and field testing. Supportive structural tests for certain large-scale applications were also described. He mentioned that a structural problem is one whose solution calls not only for information on short-term properties of epoxy resin systems, but also on their deformation under static load, behavior under continuous or dynamic stresses, behavior at elevated temperatures, and in many cases, the effect of moisture on adhesive strength. The construction engineer is interested above all else in the long-term behavior of a building material. Specifications aimed in the last analysis at providing the client and building contractor with reliable data on the selection of materials available, properties and test procedures should certainly include information on long-term behavior.

Plecnik and other researchers have published a group of papers on the effect of elevated temperatures and fire exposure on epoxy repaired concrete elements [34, 35, 36]. It was mentioned that numerous articles have been written on epoxy adhesives and epoxy repaired concrete elements under room temperature conditions, limited amounts of experimental data was available on the behavior of epoxy repaired components during and after fire exposures [34, 35, 36]. Except for elevated temperature, fire and creep effects, most strength properties of epoxy repaired concrete components exceed those prior to damage. Since epoxy adhesives are organic thermosetting resin systems, they are highly susceptible to softening and pyrolysis at elevated temperatures. The strength and behavior of epoxy repaired concrete elements at elevated temperatures are of importance in several applications. First, concrete structural elements such as beams and walls are subjected to either continuous or frequent exposure to elevated temperatures. Examples are epoxy injected cracks in (1) nuclear power plant structures; (2) decks in bridges subjected to sun exposure; (3) concrete stacks. Second, thermal gradients in epoxy repaired concrete elements generated by actual exposure to fire can reduce the strength of epoxy repaired beams, walls, and columns significantly [36].

In reference [34] the degradation of strength properties at elevated temperatures was investigated on two unfilled structural epoxy adhesives that are used for repairing cracks less than about 6.4 mm (1/4 in) and therefore this study is applicable to those epoxy adhesives of the same type and which have heat distortion temperature, strength transition temperature and zero strength temperature similar to those used in that study (approximately 80°C (180°F), 110°C (230°F), 200°C (400 F), respectively. Two types of tests were described. "Hot Tests" referred to specimens subjected to a specified time-temperature curve (1 hour duration under a specified temperature) and tested immediately after completion of heat exposure.

"Residual Tests" indicated that specimens were exposed to the one hour duration inside the oven at a specified temperature and then cooled down at room temperature for 7 days before testing them. A series of tests were performed on epoxy specimens conforming with ASTM standards of rigid plastics. Variations with respect to a temperature range from room temperature upto 204.4°C (400°F) was obtained of such properties as static compressive strength (hot and residual tests), residual dynamic compressive strength. and residual impact energy. Results of static compressive strength test on epoxy cylindrical specimens of 12.7 mm. (½ in) diameter and 25.4 mm (1 in.) length showed larger values for residual test than those of hot strength test. In general, both showed degradation as the temperature of the one hour exposure increased (Fig. 2.6). Since the compressive tests utilized laterally unconfined specimens, the "residual" strength properties of structural epoxy adhesives confined with thin cracks may be considerably different from those indicated in Fig. 2.6 especially at temperatures near and above 200°C (400°F). A series of static tensile and shear strength tests were also conducted on unfilled structural epoxy adhesives and described in earlier publications mentioned in the same reference. These results also showed that a drastic reduction of tensile and shear strength properties occured at the strength transition temperature. Beyond 200°C (400°F), all "hot" strength properties became negligible for the type of epoxy adhesives mentioned above. The effect of specimen size and configuration on both the "hot" and "residual" strength properties

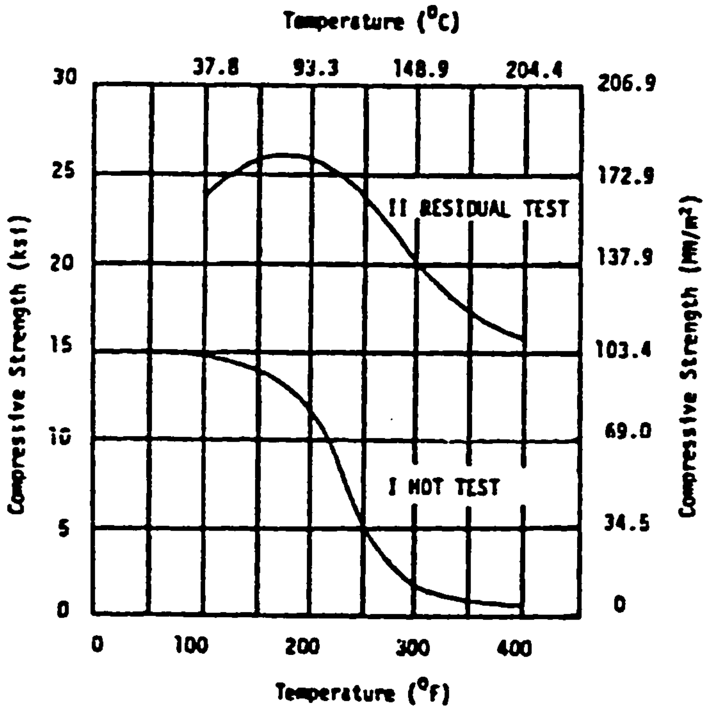


Fig. 2.6: **Average Static Compressive Strength Results for the Structural Epoxy Adhesives Provided in Reference [34]. Source : Reference [34]**

was appreciable [34].

Many concrete structures transfer lateral wind or seismic loads through bearing or non-bearing shear walls. In reference [35] Plecnik and others studied experimentally the strength properties and other important parameters of epoxy-repaired concrete walls during and after "pseudo-type" building fire exposures.

Flexural tests on small and large size epoxy repaired concrete beams of shear and flexural type failures tested at elevated temperatures and under fire conditions were reported in reference [36]. Small-scale beams were subjected to uniform temperature exposures for 2.5 hours after the injected epoxy had been curd. "Hot" and "residual" strength tests were applied in the temperature range of 23.5-204°C (75-400°F) and ultimate load and stiffness values were recorded. It was found that the behavior of epoxy repaired concrete beams degraded as the exposure temperature of the specimens increased. Test results also showed that both short-term strength and stiffness of epoxy repaired beams reduced rapidly at uniform temperatures exceeding about 121°C (250°F). Large-scale beams were subjected to prescribed "pseudo-type" fire exposures and tested to the ultimate strength after the end of fire exposure. It was found that under fire conditions, the strength reduction is primarily influenced by the presence or lack of fire protection coatings and the thermal gradients [36].

Fattuhi [23] examined the effect of temperature on the flexural strength of pre-notched (simulated crack) beam specimens repaired with three different adhesive materials, including an epoxy resin, and the tensile splitting test of cylinders formed by bonding two longitudinal half cylinders with the same repair materials. The results indicated that the effectiveness of the repair materials in transmitting the tensile stresses across a crack was reduced considerably when the air temperature was increased from 20°C to 63°C (68°F to 145.4°F). Decreases in modulus of rupture and splitting tension of nearly 50% and 23% respectively were reported.

Schupack [37] showed the importance of long-term performance of epoxy-coated composites. When epoxy or epoxy-mortar layers had been laminated with concrete in thicknesses of (6 mm) (1/4 in) or more, distress had sometimes occurred. Distress was caused by differences in the shrinkage, thermal and mechanical properties of the two materials. He mentioned that a single high thermal shock sometimes could degrade the composite, as can any of various cyclic changes over a period of time. He presented three case studies of epoxy-coated composites in which distress occurred after several years at the interface of epoxy and concrete. Severe environments causing repetitive cycles such as heat-cool cycling, wet-dry cycling, and/or freeze-thaw cycling were mainly responsible for these distresses. Differences in volume changes due to the cycling effect, and using epoxy without enough creep characteristics and small enough modulus of elasticity to accommodate these volume change differences without introducing excessive stresses, resulted in fatiguing the materials even though the stresses might have been small. He mentioned that the ASTM test methods, C883, "Standard Test Method for Effective Shrinkage of Epoxy-Resin Systems Used with Concrete", and C884 "Standard Test Method for Thermal Compatibility Between Concrete and Epoxy-Resin Overlay", try to measure any differences in volume change characteristics, but the behavior observed in the distress cases cited there suggested that the methods might be inadequate. Epoxies used there were supplied so long ago that it was not possible to apply these tests on the original lots of epoxies for guidance as to their suitability. He suggested at the end of his article that it would be of interest if the cases of distress mentioned could be duplicated in the laboratory and monitored so that the actual cause of deterioration could be understood clearly. From this type of controlled investigation the do's and don'ts of epoxy-concrete composite laminates could be better established [37].

To clarify the long-term behavior of reinforced concrete structural elements strengthened by structurally bonded reinforcement, a special test program with bonded external reinforcement on concrete structures at the Swiss Federal laboratories for Materials Testing and Research at Duckendorf (EMPA), was set up with a planned observation for at least 15 years. Initial information obtained after one, three, and five years are reported in reference [38].

Ciba-Geigy in its publication titled "Araldite Structural Adhesives Supplied by Ciba-Geigy" provides information about which Araldite adhesive is the best choice for a given job, along with a collection of useful characteristics of the group of Araldite adhesives mentioned therein. Among those characteristics are some information on the short-term and long-term bond strengths of Araldite adhesives. Short-term bond strength included lap shear strength of typical metal-to-metal joints at 23°C (73.4°F),and lap shear strength versus temperature in the range of 60°C to 140°C (140°F to 284°F) for the group of adhesives. It was mentioned that unstressed assemblies bonded with an Araldite adhesive would withstand temperatures upto 200°C (392°F). After cooling, the bonded joints would exhibit the original as-made properties. Long-term bond strength involved two types of strength tests: the first is the static load bearing strength versus temperature with a test duration of 10,000 hours. It was stated there that "for Safety's sake, the long-term strengths of the standard adhesives not shown should be taken to be 20% of their short-term strength". The second type of test is the dynamic load bearing strength at 23°C (73.4°F) as a percentage of short-term shear strength for varying number of loading cycles with a maximum of 10^7 loading cycles. It was also mentioned that "for safety's sake, the dynamic load bearing strength of the standard adhesives not shown should be taken to be 20% of their short-term strength at $n = 10^7$". Finally this publication demonstrated the proper design of bonded joints. It stated "bonded joints should be designed so as to exploit fully the properties of the adhesive. If failure occurs, it should be in the material bonded, not in the glue line. This aim is best achieved by designing joints so that they will be subjected to shear, compressive, or pure tensile stresses. Eccentric tension and peel loading should be avoided". This is explained in Fig. 2.7 [39].

2.2 Scope and Objectives of the Study

2.2.1 Present Status of the Problem

From the literature review in Section 2.1 it is clear that short-term properties of epoxy injected concrete are quite satisfactory. However, long-term properties are of more concern for the construction engineer. Also, high temperature exposures have a considerable adverse effect on concrete repaired by epoxy injection on the short-term and have a more deleterious effect on the long run. Repetitive cycling such as heat-cool and wet-dry cycling can lead to fatiguing these composites over a period of time even at small stresses. Application of epoxies without enough creep characteristics and small enough modulus of elasticity to accommodate these volume change differences without introducing excessive stresses will lead to failure of such composites faster under such severe conditions.

The Arabian Gulf area in general and Saudi Arabia in particular are characterized by severe weather conditions of high

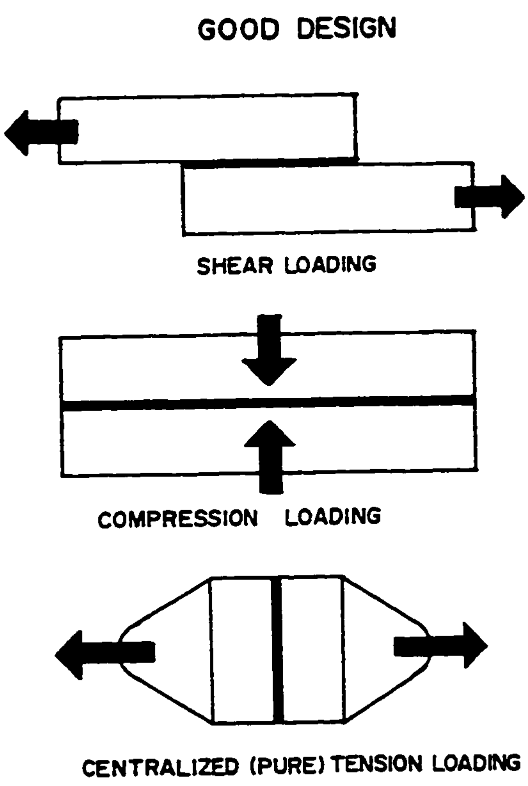


Fig. 2.7: **Design of Joints**
Source: Reference [21]

temperature exposure and high seasonal and diurnal variations of temperature and humidity. A large number of concrete structures are currently in need of repair of some type. A good percentage of these structures can be protected against deterioration by crack injection. At the same time, there is a large number of epoxy products available in the local market. Yet, there is no practical data available on the field performance of such epoxies under the severe environmental conditions of the region. There is also a clear need for a selection criteria which will help in choosing the proper epoxy product to suit the field conditions and requirements of the job. Furthermore, there are no local standards available for epoxy systems used with concrete, that take into account the characteristics and severity of the environment in this region.

2.2.2 The Role of the Study

This study is intended to examine and evaluate the performance of epoxy injected concrete under the severe environmental conditions of the region mentioned above by running an experimental program in the laboratory under simulated conditions to those of actual environment. Three different and locally available epoxies which are used in the field for crack injection were selected for this study.

Similar to ASTM C-882 [16] half concrete cylinders, each with a slant surface of 30^0 angle from vertical, are joined together so that each pair of these concrete halves forms a concrete cylinder of 76.2

mm (3 in) diameter and 152.4 mm (6 in) height with a slant gap (simulated crack) of 1.6 mm (1/16 in) thickness (Fig. 2.8). These cylinders are repaired by epoxy injection, and after suitable curing of the epoxy compounds they are exposed to simulated environmental conditions. After that they are tested in compression, where the bond between epoxy and concrete is subjected to combined compression and shear. Also, beam specimens similar to those of Fattuhi [23, 24, 25] with dimensions 152.4mm x 152.4mm x 533.4mm (6 in x 6 in x 21 in) and a notch (simulated crack) at the center of dimensions 152.4 mm (6 in) width, 76.2 mm (3 in) depth through the tension zone, and 1.6mm (1/16) in) thickness (Fig. 2.9). These beams are repaired by injecting epoxy into these notches. After curing they are exposed to simulated weather conditions, and then tested in flexure. Suggestions and recommendations related to the selection criteria of the proper epoxy products used in the region will be developed. Also, the suitability and convenience of the two evaluation techniques used in this study (cylinders and beams) will be assessed. Thus, paving the way for future studies on epoxy resins to select the proper technique for evaluation of bond properties under a given set of conditions. Therefore, through this study the following will, hopefully, be achieved:

1) Cylinders will be subjected to a temperature increase upto (70°C) 158°F for a period of 6 hours in the oven, and then tested immediately in compression while they are hot (hot

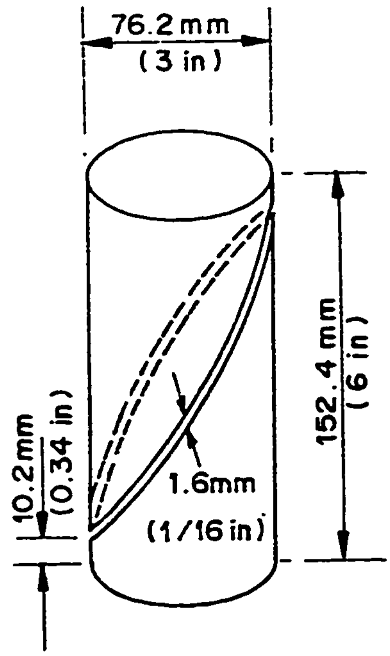


Fig. 2.8: Concrete Cylindrical Specimen for Epoxy Injection

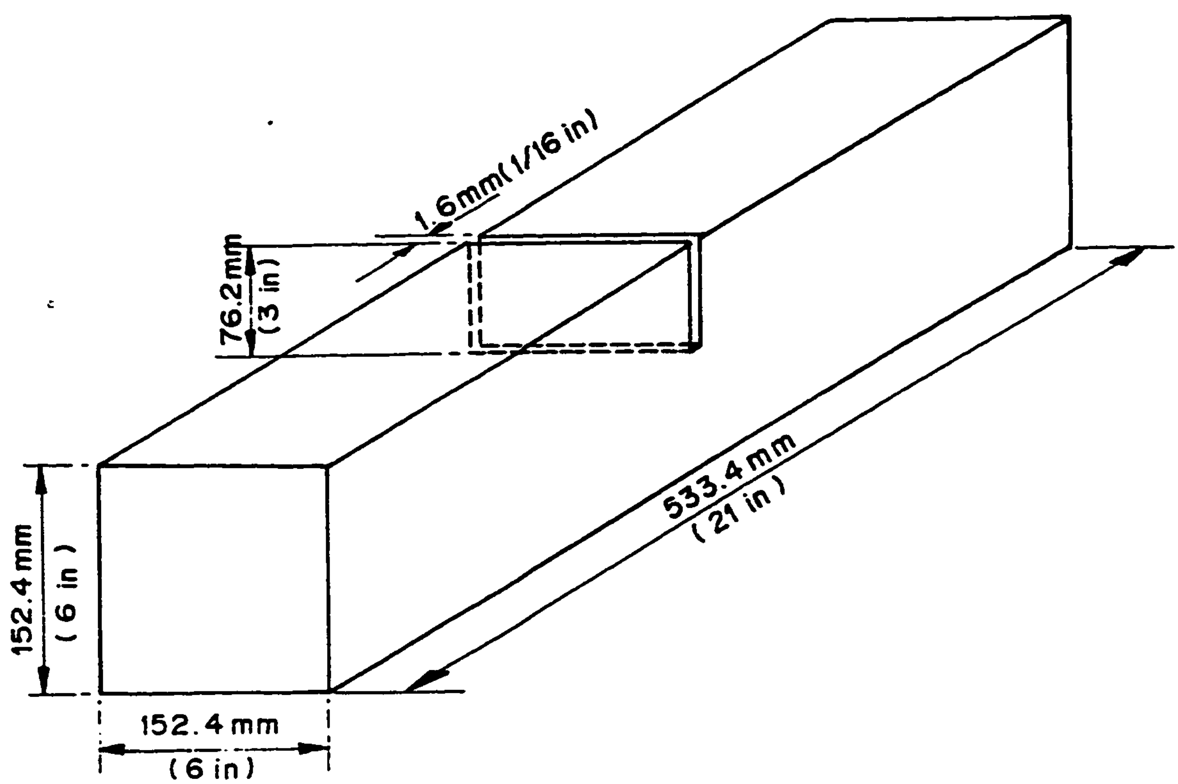


Fig. 2.9: Concrete Beam Specimen for Epoxy Injection

strength test and short term property).

2) Cylinders will be subjected to a heat-cool cycling program before they are tested in compression while they are cool (residual strength test and long-term property). They will be subjected to 0, 50, 100, 150 heat-cool cycles and each cycle consists of 6 hours in the oven, where the temperature is set at 70°C (158°F) and 6 hours at room temperature 20°C (68°F), where the specimens cool down gradually.

3) Cylinders will be subjected to a wet-dry cycling program before they are tested in compression while they are cool and dry (residual strength test and long term property). They will be subjected to 0, 80, 120 wet-dry cycles and each cycle consists of 12 hours immersion in water, 6 hours in oven, where the temperature is set at 70°C (158°F), and 6 hours at room temperature 20°C (68°F), where the specimen cools down gradually.

In the above three programs each point with a given set of conditions is represeted by 8 cylindrical specimens: 2 complete reference cylinders 2 epoxy injected cylinders for each type of the three epoxies used. The average of two specimen readings is considered in the analysis of data.

4) Beams will be subjected to a temperature increase upto 70°C (158°F) for a period of 6 hours in the oven, and then tested immediately in flexure while they are hot (hot

strength test and short term property).

5) Beams will be subjected to a heat-cool cycling program before they are tested in flexure while thy are cool (residual strength test and long term property). They will be subjected to 0, 50, 100, 150 hot-cool cycles, and each cycle consists of 6 hours in the oven where the temperature is increased upto 70°C (158°F) and 6 hours at room temperature 20°C (68°F) where the specimen cools down gradually.

In the above two programs on beam specimens each point with a given set of conditions is represented by 10 beam specimens: 2 ungrooved reference specimens, 2 grooved unrepaired reference specimens, 2 epoxy injected beam specimens for each type of the three epoxies used. Also, the average of two specimen readings is taken in the analysis of data.

A general flow chart for the main steps in this study is shown in Fig. 2.10.

Literature Review
and Setting of
Experimental Program

Preparation of
Molds and Materials

Casting of Beams
and Cylinders

Repair of Beams
and Cylinders

Exposure to Simulated Local
Environmental Conditions

Testing of Beams
and Cylinders

Analysis of Data
and
Discussion of Results

Conclusions
and
Recommendations

Fig. 2.10: General Flow Chart for the Main Steps in this Study

Chapter 3

EXPERIMENTAL PROGRAM

3.1 General

The experimental work of this study was carried out in the laboratories of the Civil Engineering Department of the University. Throughout the experimental program ASTM standard specifications for concrete and construction [40] were followed. A flow chart for the general outlines of this study is shown in Fig. 2.10. A more detailed flow chart is shown in Fig. 3.1. Details of the different activities of the experimental program of this work are provided in the following sections.

3.2 Preparation of Molds and Materials

3.2.1 Molds

Molds were prepared to confirm to ASTM standard specification C192-81, entitled "Standard Method of Making And Curing Concrete Test Specimens In The Laboratory".

3.2.1a Molds for Cylinders:

Standard steel cylinders were used to produce 154.4mm x 76.2mm (3 in x 6 in) concrete cylinders. Wooden cylindrical speci-

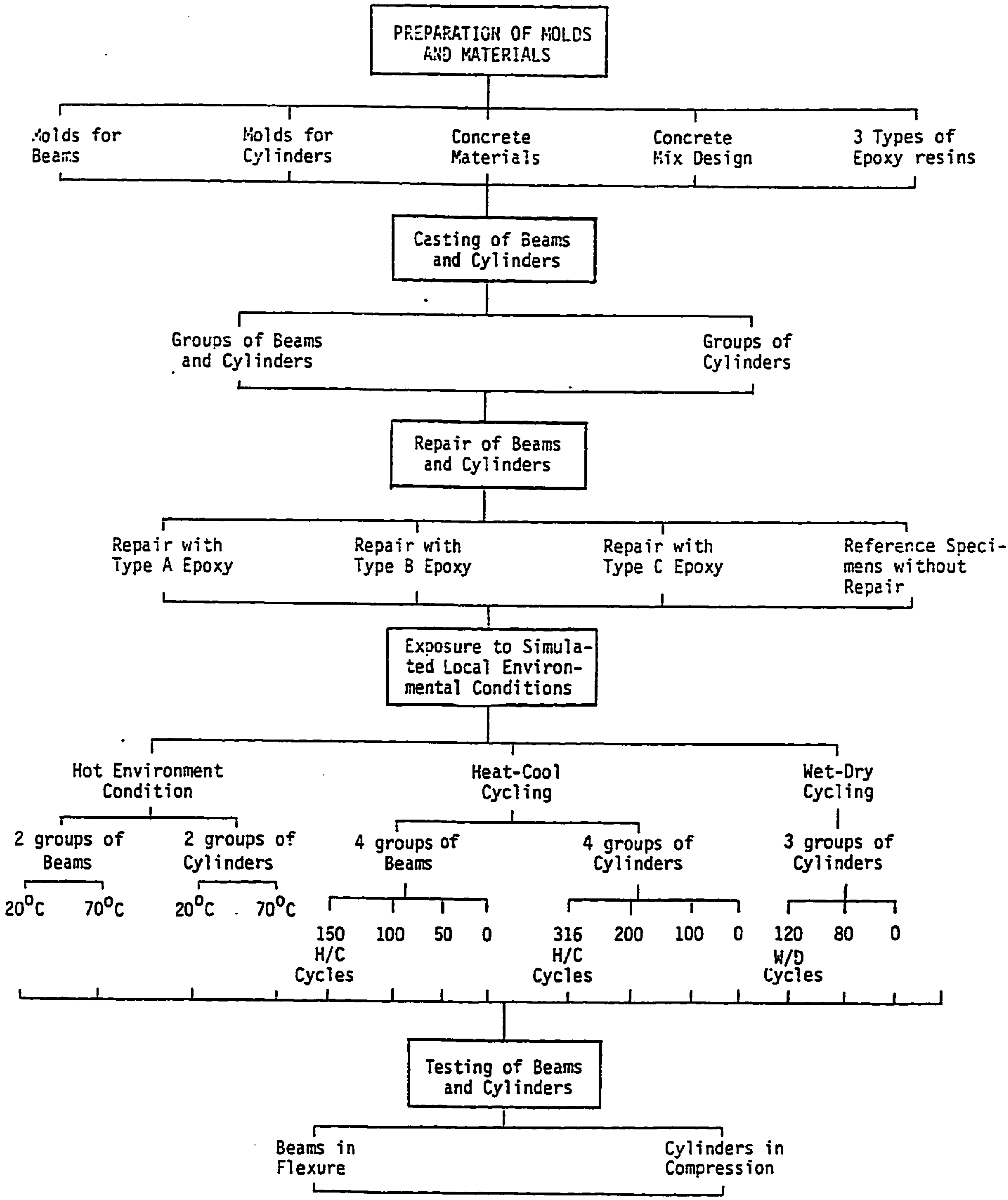


Fig. 3.1: Detailed Flow Chart of the Experimental Program

mens of 76.2mm (3 in) base and 152.4mm (6 in) height and a slanted surface running diagonally making an angle of 30^0 with the vertical were prepared in the mechanical workshop so that when placed inside the steel molds, slanted half concrete cylinders of the same dimensions could be casted (Plate 3.1), (Fig. 2.8). Steel and wooden molds were prepared so that group of (12) half cylinders could be casted along with two full compression cylinders for quality control. Therefore, a group of eight cylinders could be casted together which would be exposed to a given set of conditions.

3.2.1b Molds for Beams:

Two wooden molds were prepared in the mechanical workshop for the preparation of beam specimens. Each mold could produce four beam specimens, each of which has the dimensions of 152.4mm x 152.4mm x 533.4mm (6 in x 6 in x 21 in) (Plate 3.2), (Fig. 2.9). Eight metal notches of dimensions 152.4mm x 76.2mm x 1.6mm (6 in x 3 in x $\frac{1}{16}$ in) were also prepared in the workshop so that they could be fixed on the wooden molds to produce eight beams having notches at their centers, each notch is of 1.5 mm ($\frac{1}{16}$ in) thickness, running throughout the width of the beam (154.4 mm = 6 in) and of depth equal to half the depth of the beam (76.2mm = 3 in). Two additional steel molds were used for producing ungrooved complete beams of the same dimensions. Hence ten beams representing one group of a single set of conditions could be casted together.

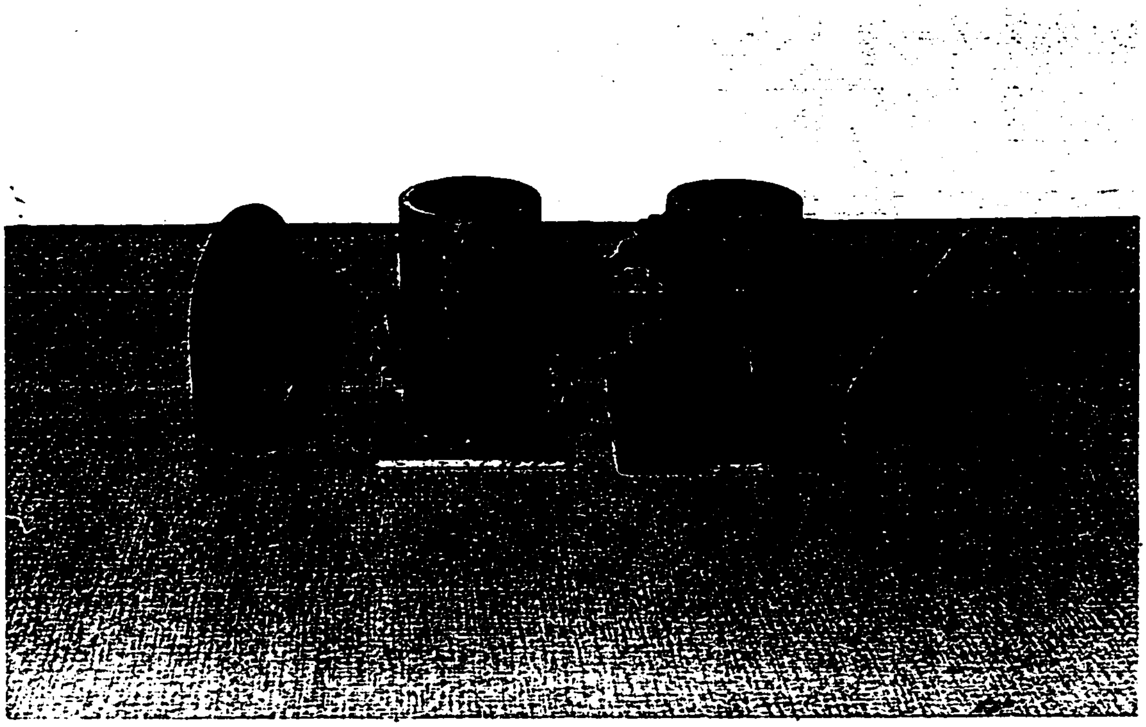


Plate 3.1: The steel mold and dummy wooden specimen for producing slanted half concrete cylinders.

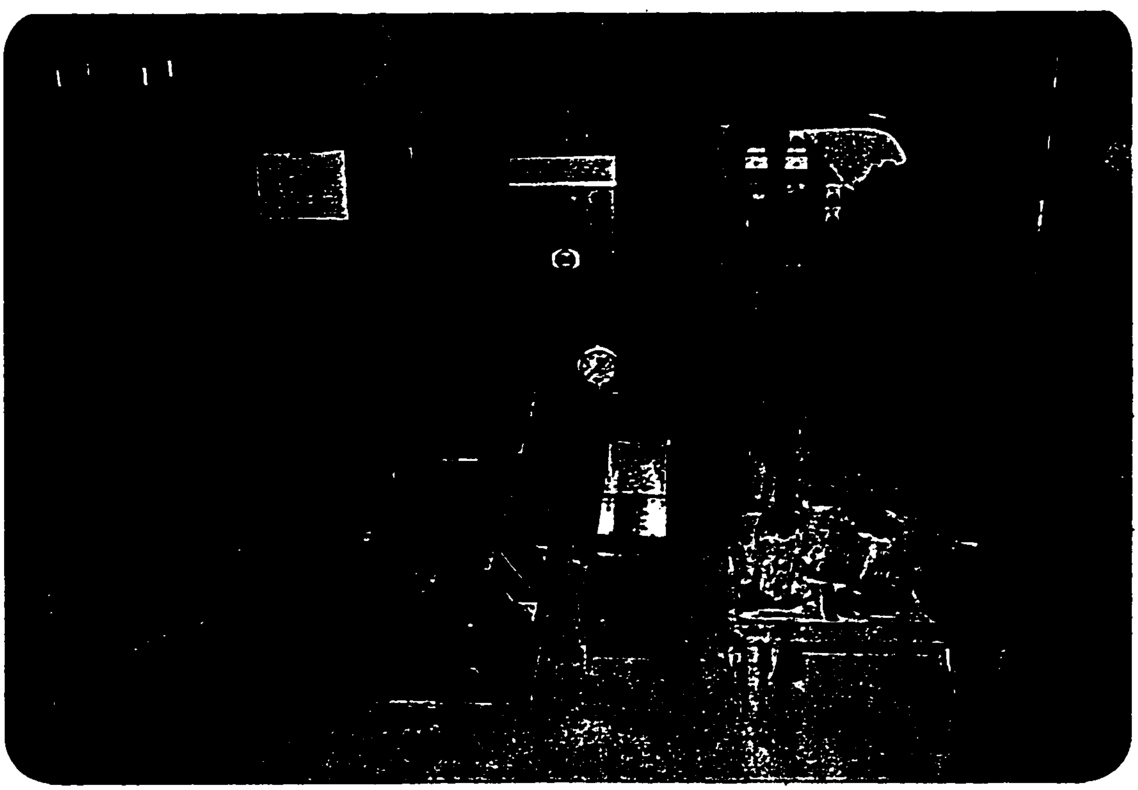


Plate 3.2: Molds of beam and cylinder specimens ready for casting.

3.2.2 Materials

Three types of epoxy resins for injection of concrete cracks were selected for this study. They are manufactured in Europe and available in the local market as they are among the more widely used in this region. Table 3.1 shows the brand names of these products along with their manufacturer addresses. Table 3.2 shows some of the important properties of these epoxy products as obtained from manufacturer's instruction sheets. These three types of epoxy resins are designated by epoxy A, epoxy B and epoxy C, hereafter.

Epoxy product A was provided in a kit containing 10 cartridges of the resin material and 10 tubes of the hardener in addition to a set of auxiliary materials needed for injection such as injection nipples with locating pins, nipple caps, and lengths of hoses. Epoxy product B was available in packages, each of which contained premeasured can of epoxy resin and a can of hardener weighing together 2 kgs. Epoxy C was available in big separate cans of resin and hardener.

Also, another two-component prepacked adhesive based on Araldite epoxy resin (EP-CA) was used as a sealant for the cracks before starting the injection process. It has its own properties such as long pot life, high viscosity, and enough mechanical strength, which are suitable for its function as a sealant. A simple injection equipment was used for the injection of the three types of epoxy. It was composed of a hand actuated gun, standard empty paint cartridges, lengths of hoses, and nipples as entry and exit ports (Plates 3.3, 3.4).

Table 3.1: A List of Epoxy Resins Used in the Study

Epoxy Code	Product Name	Manufacturer and Address
A	EP-IS Epoxy Injection System	CIBA-GIEGY Switzerland
B	Sikadur 52 Injection	Sika Switzerland
C	BERODUR EP-INJECT	EUROTEAMAG Berlin, West Germany

Table 3.2: Properties of the Three Types of Epoxy Resins Used as Obtained from Manufacturer Instruction Sheets

Property	Epoxy A	Epoxy B	Epoxy C
Type of Epoxy	Two component injection system based on Araldite epoxy resins	Solvent free, low viscosity Two component resin injection on an epoxy-resin basis	Solvent free, low Viscosity Two component epoxy resin system
Typical field of application	Repair of Cracked concrete, consolidation of friable rock or stone	Priming, sealing and injection of cracks in horizontal and vertical constructions	Rigid compressive filling of cracks in concrete and masonry
Storage Conditions and Shelf life	Resin and hardener have a shelf life of one year if stored at 15-25°C (59-77°F). The reactivity of products which have been in storage for more than a year should be tested before use.	+5°C to + 40°C. A shelf life of 12 months when unopened and stored correctly	Dry and Cool, minimum storage period of 6 months
Working Temp. (Processing Temp.)	15°C to 30°C (59 to 86°F)	5-10°C (41-50°F)	Min 5°C (41°F)
Pot Life	110 min at 10°C(50°F) 50 min at 23°C(73°F) 25 min at 30°C(86°F)	50 min at 10°C(50°F) 20 min at 20°C(68°F) 10 min at 30°C(86°F)	30 min at 20°C(68°F)

Viscosity	300 mPa s at 10°C(50°F) 110 mPa s at 23°C(73°F) 70 mPa (s at 30°C(86°F)	500 C.Poise at 20°C(68°F) for normal type 250 C.Poise at 30°C(86°F) for normal type 290 C.Poise at 20°C(68°F) for L.P. type 130 C.Poise at 30°C(86°F) for L.P. type	160 mPa s 25°C(77°F)*
Specific Gravity		1.1 g/cm^3	Approx. 1.2 g/cm^3
Minimum Curing Time	24 hours at 18°C(65°F) 6-8 hours at 23°C(73°F)		
Mechanical Properties:	After curing for 7 days at 23°C(73°F)		
Compressive Strength	(ISO/R 604) 80 N/mm^2 (11,600 psi)		Approx. 97.4 N/mm^2 (14124 psi)
Tensile Strength	(ISO/R527) = 60 N/mm^2 (8700 psi)	25 N/mm^2(3625 psi) N/L.P.	61.9 N/mm^2(8976 psi
Flexural Tensile Strength			103.1 N/mm^2(14950 psi)
Elastic Modulus	(ISO/R527) = 3200 N/mm^2 (464,200 psi)		E-Modulus/bend 2510 N/mm^2(363983 psi)

Bond Strength		To concrete 3.5 N/mm^2 (5088psi)(concrete failure) To steel 10-15 N/mm^2 (1450-2175 psi) (20°C=68°F, 65%RH, 10 days)(Steel sand blasted)	The bonding of concrete is stronger than the tensile strength of the concrete itself. For steel the tensile strength is over 8.0 N/mm^2(1160 psi)
Shear Modulus			Concrete (dry) Approx. 8.0 N/mm^2 (1160 psi) Concrete (wet) Approx. 1.9 N/mm^2 (276 psi)
Adhesion to damp concrete	Good	Can be applied	
Bending Strength			10.3 mm
Impact Resistance			19.7 mm N/mm^3
Elongation			9% after 7 days
Coefficient of Thermal expansion,	60×10^{-6} per°C (33.3×10^{-6} per°F)*	90×10^{-6} per°C (50×10^{-6} per°F)*	50×10^{-6} Per°C (27.8×10^{-6} per°F)*
Important recommendations		Maximum width of crack = 5mm(0.197 in) Minimum age of new concrete = 3-6 weeks.	

Footnote:

* Obtained from manufacturer on request.

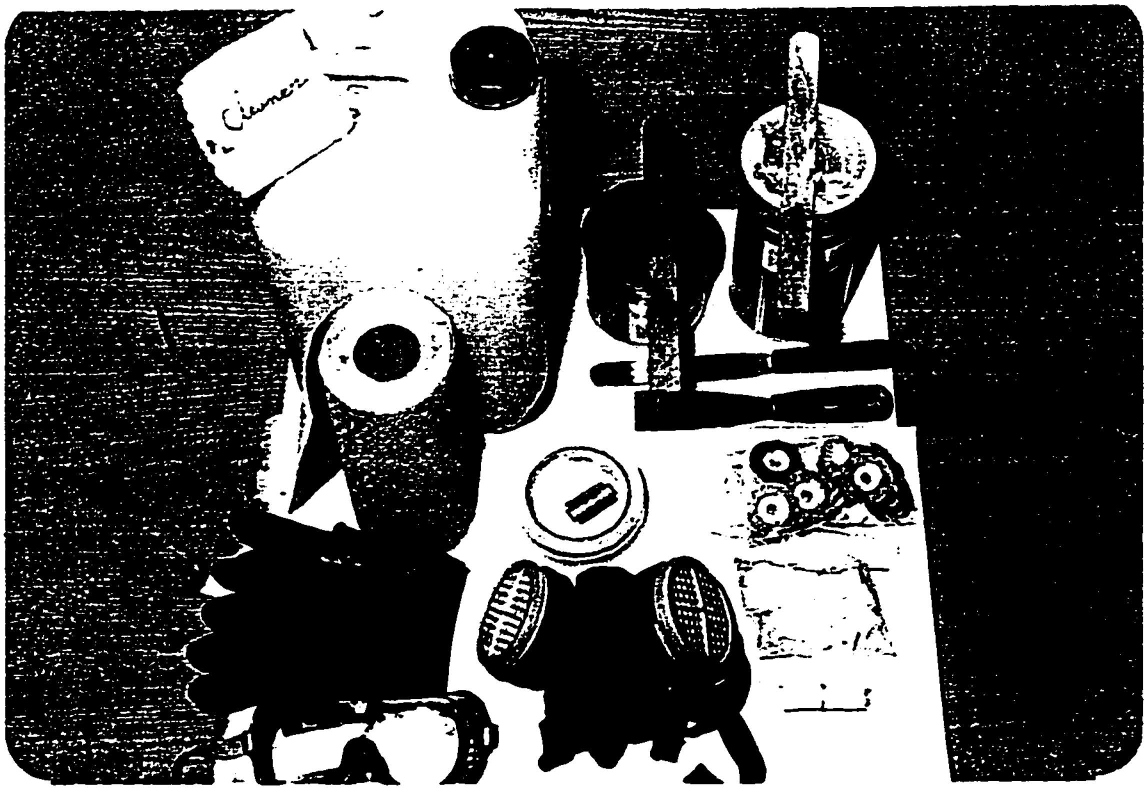


Plate 3.3: Materials used for the sealing of cracks before epoxy injection.

Plate 3.4: Materials used for the repair of cracks by epoxy injection.

3.3 Casting of Beams and Cylinders

ASTM C-192 standard method of casting and curing concrete test specimens in the laboratory [41] was followed. A concrete mix design with the following properties by weight was used:

Ordinary Portland Cement	: 1
Eastern Province Beach Sand	: 1.39
Abu-Hadriyah Crushed Aggregate	: 2.85
Water (potable)(w/c=0.52)	: 0.52

Coarse aggregates were proportioned to conform to ASTM C 33-66 grading limits of size No.7, with the following percentages:

Coarse aggregate retained on 1/2" sieve	: 11.72%
Coarse aggregate retained on 3/8" sieve	: 39.51%
Coarse aggregate retained on No.4 sieve	: 48.78%

It was required to cast beam specimens for heat/cool (H/C) cycling and hot (HOT) conditions and cylindrical specimens for (H/C), wet/dry (W/D) cycling and (HOT) conditions. It was also intended to cast each group of specimens, which would be exposed to a certain number of cycling condition together in order to restrict the variation in the results on the factors under consideration. This trend was followed throughout this experimental work. Due to the limited capacity of the drum mixer used, specimens were casted as mentioned in the following sections.

3.3.1 *Casting Beams and Cylindrical Specimens for (HOT) Conditions*

Materials were prepared and molds were fixed and oiled. Metal notches were fixed at their locations in beam molds and the dummy wooden slanted specimens were put into the steel cylinders. For this group of beams and cylinders, which would be tested while hot at a specific temperature, thermocouple wires were embeded into the core of each of its beam and cylindrical specimens for measuring the concrete temperature of the hot specimens before and after the test. It was decided to locate them away from the middle third in the case of beams to avoid any effect of their presence on the testing results. For cylinders, they were located at the core of the complete cylinder or at the core of the slanted half specimen. Thermocouples would be added also to the cracks filled with epoxy for the same purpose. The group of 10 beams and 8 cylinders were casted on 2 successive intervals. Firstly, concrete for five beams was prepared in the drum mixer. After measuring the slump, concrete was casted in the molds in one layer, according to ASTM C-192, and thermocouple wires were added. The beams were vibrated using a vibrating rod. The surface of concrete was levelled and covered by polythene sheets. Secondly, the drum mixer was cleaned and prepared for the 2nd mix. Concrete materials enough for another 5 beams, 2 complete cylinders and 6 x 2 slanted half cylinders were mixed together in the mixer and placed in the molds. Beams were treated in the same manner and cylinders were filled in two layers. Thermocouple wires were embeded and cylinders were vibrated using the vibrating table, levelled, and covered with polythene sheets. Compression cylinders for quality control were also prepared in both mixes. Three days later, when concrete had gained enough strength, metal notches were removed smoothly, and specimens were demolded with particular care for the half cylindrical specimens, and all specimens were placed in a water tank for the rest of the 28 days curing time.

Another group of beams and cylinders was casted in the same manner, which would be tested at normal conditions, i.e. at room temperature and without heating or cycling. This group of beams and cylinders would be actually representing reference result values for the other groups which would be exposed to high temperature during testing or cycling program before testing them while cool.

3.3.2 Casting (H/C) Beams and (W/D) Cylinders

The above two successive castings that were used to produce one group of beams and cylinders were repeated three times similarly in order to produce other three groups of beams and three groups of cylinders. No thermocouples were used since specimens would be tested while cool at room temperature. The three groups of beams would undergo a heat/cool (H/C) cycling program, while the cylinders would be exposed to wet/dry (W/D) cycling procedure after repair.

3.3.3 Casting (H/C) Cylinders

Three groups of cylinders were needed for the heat/cool (H/C) cycling program. Each group was casted separately with the same mix design proportions and consisted of eight cylinders (2 complete cylinders and 6 x 2 half slanted cylinders) with addition to three quality control cylinders and two additional half cylinders. The casting process proceeded in a similar manner to that of (W/D) cylinders.

3.4 Repair of Beams and Cylinders

The next step was the repair of beams and cylinders. Following the manufacturer instructions of each type of epoxy is important. Safety precautions were exercised during the applications of these epoxy materials.

3.4.1 Repair of Beam Specimens

The following procedure was followed for all groups of beam specimens:

1) Surface Preparation: when the group of beams were taken out of water after curing, crack surfaces of beam specimens, which would be used for crack injection, were prepared to remove the oil spots and be little roughened. A piece of cloth was passed through the beam crack while it was in the water tank and rubbed its surfaces. Then it

was removed from water and both surfaces of the crack were roughened by rubbing them using a very thin saw blade three times on each surface followed by a very rough emery cloth for fifteen times on each surface. After that the crack was cleaned by jetting clean water into it. The beam was left for at least five days in the laboratory for drying and lastly, the crack was cleaned by jetting dry air into it just before sealing it (Plate 3.5). All the rest of the group beam specimens received the same treatment.

2) Sealing the Crack Surface: A piece of thin tape was placed on the boundary of the crack to further safeguard the sealing material from going into the crack itself. A bonded flush fitting with a hat-like shape (nipple) was used for the entry of injected epoxy. It was placed at the lowest point of the crack on one of the sides of the beam under consideration. A similar port for the exit of epoxy after filling the crack was formed using the sealing material at the highest level of the crack on top of the beam at the other side from the entry port. The sealing material was prepared by mixing its two components together and used to fix the nipple, form the exit port, and seal the crack boundaries by applying a layer on top of the tape and around it. After that beams were left for curing and epoxy injected in the next day. (Plate 3.6).

3) Epoxy Injection: Materials and equipments needed were

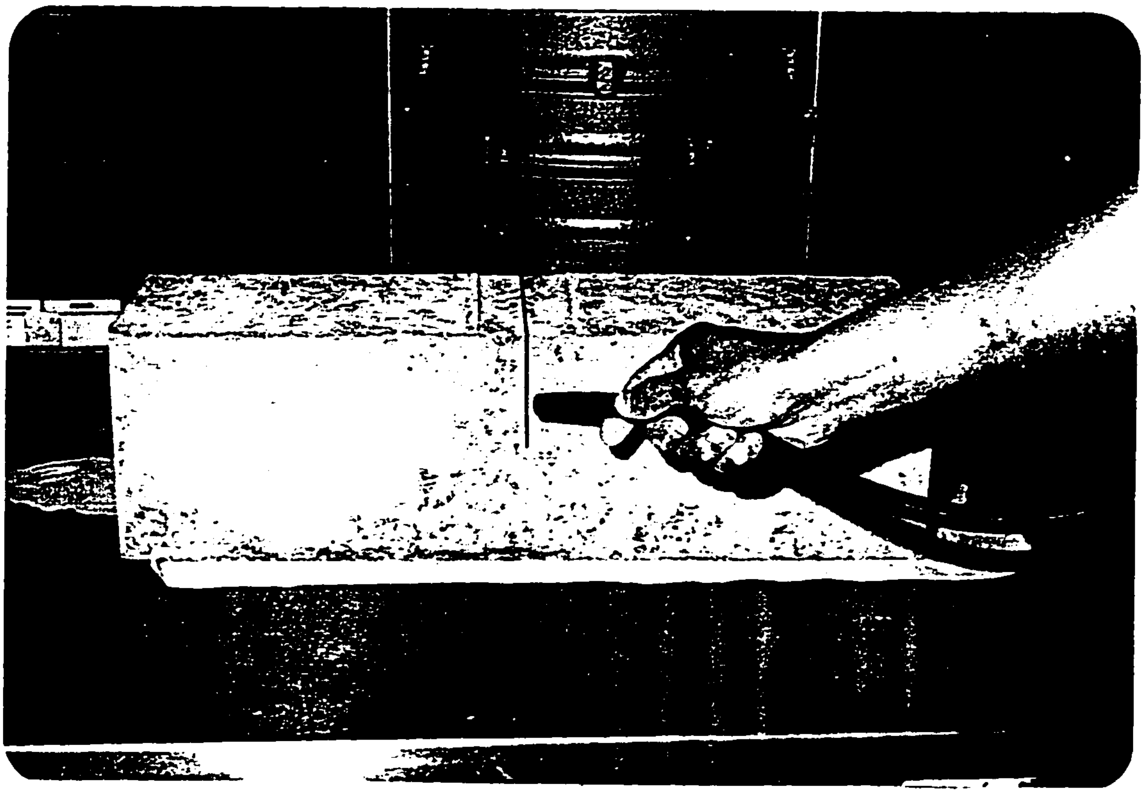


Plate 3.5: Cleaning the crack surfaces by air pressure before repair.

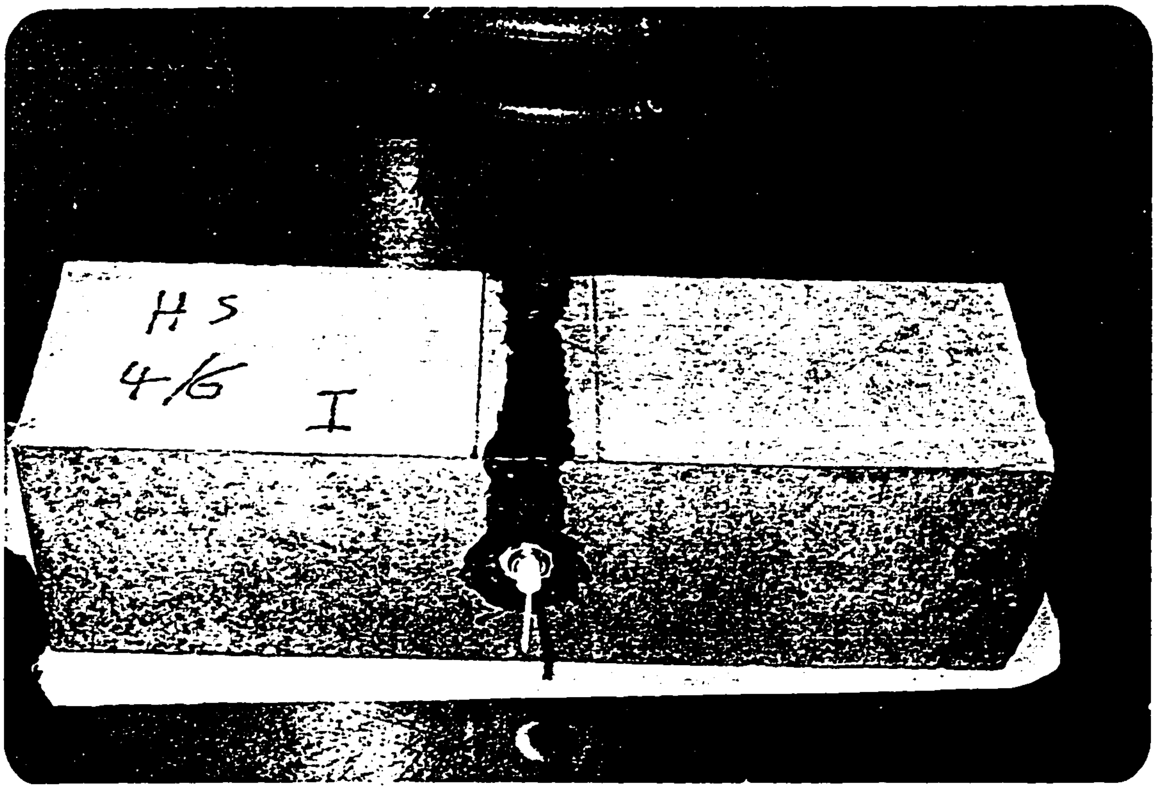


Plate 3.6: A beam specimen after sealing the crack and before epoxy injection.

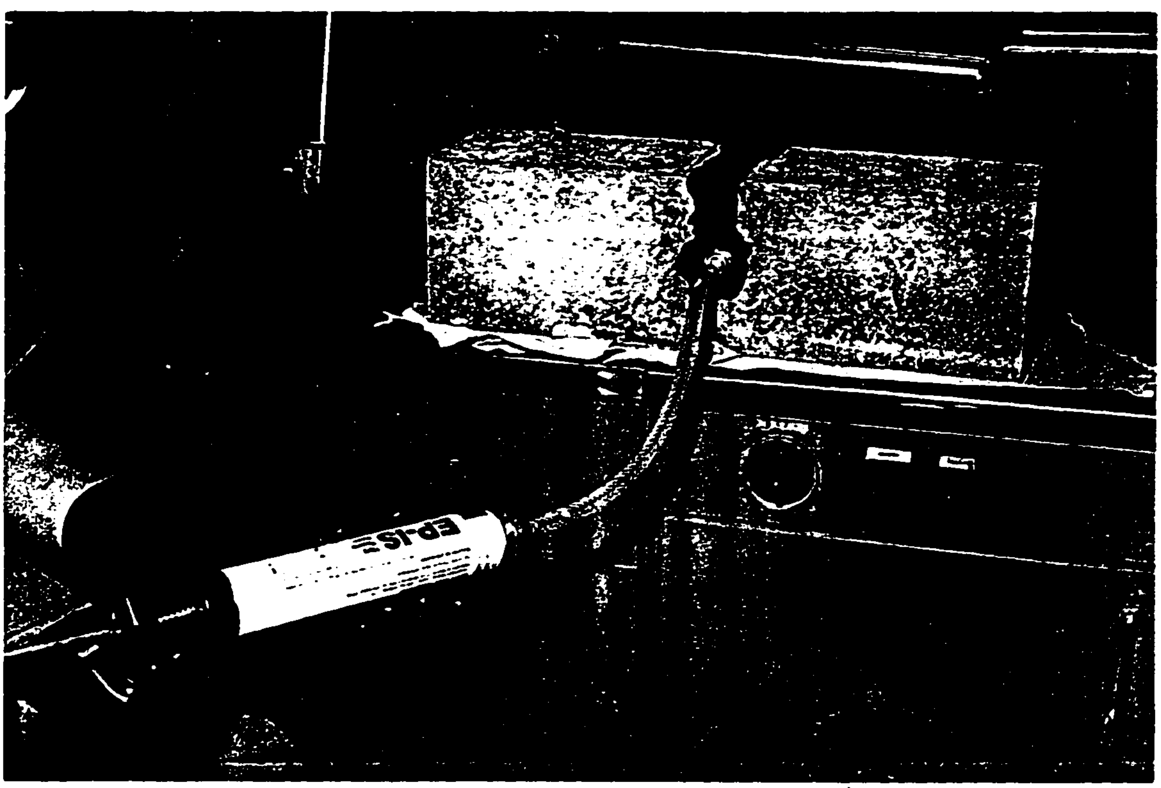


Plate 3.7: A beam specimen during the process of epoxy injection.

prepared first. Each epoxy of the three types was prepared by mixing its two components thoroughly before applying it. Type A epoxy was mixed by pouring the tube of hardener into the cartridge of resin and shaking it properly a number of times. Epoxies of types B and C were mixed in a beaker using an electric stirrer and then poured into empty paint plastic cartridges. Epoxy injection was performed slowly using a hand actuated gun in order to press the epoxy from the cartridge to the entry port passing through a plastic hose (Plate 3.7). When it appeared from the upper exit port the lower nipple was closed with a cap and epoxy was given a curing period of at least seven days before proceeding to the next stage (Plate 3.8). Each epoxy was used to repair two specimens from each group of beams as mentioned earlier, and frequently beams and cylinders of more than one group were injected together by the same epoxy in order not to waste prepacked quantities and also to save time.

4) <u>Removal of the Sealant</u>: After curing of epoxy and as it is usually the case in practice, nipples were struck off and the sealant was removed using a hand grinder (Plate 3.9). That would exclude any effect of the sealant strength during testing the specimens. It was taken into consideration not to cause too much heat at a point during grinding so that the bond between epoxy and concrete would not be

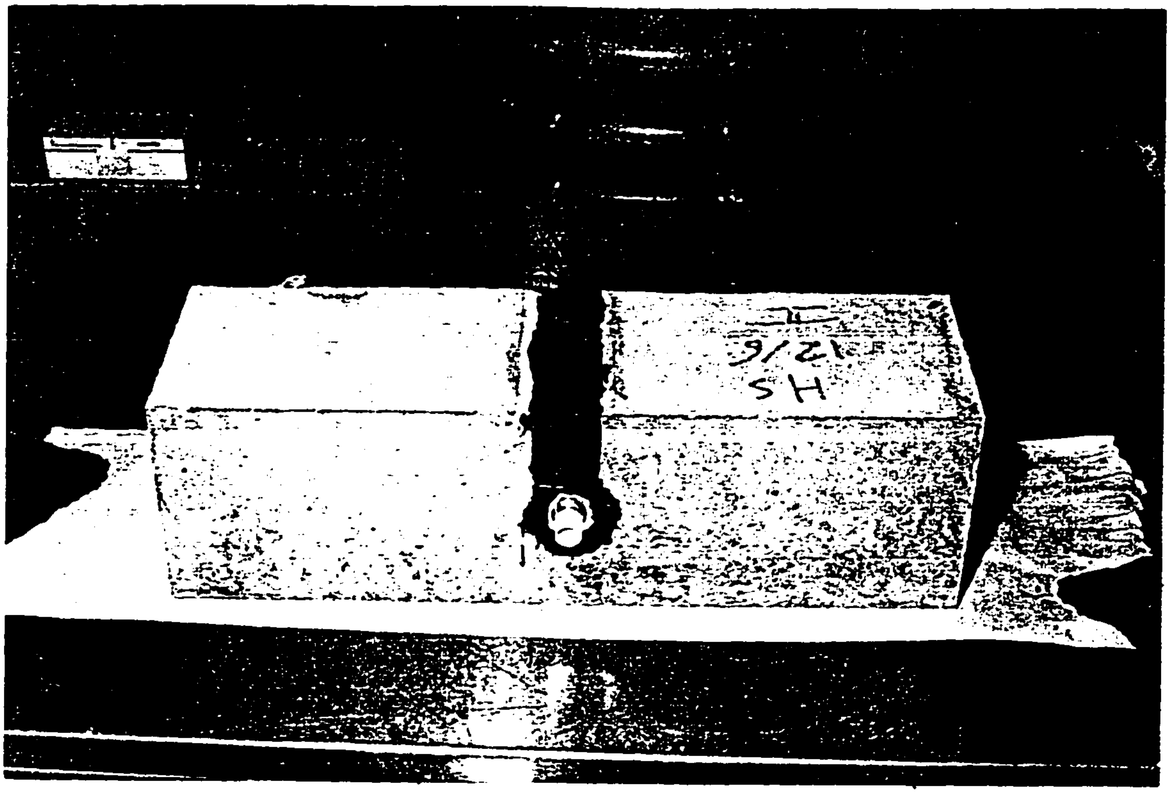


Plate 3.8: A beam specimen after repair, left for curing of the injected epoxy compound.

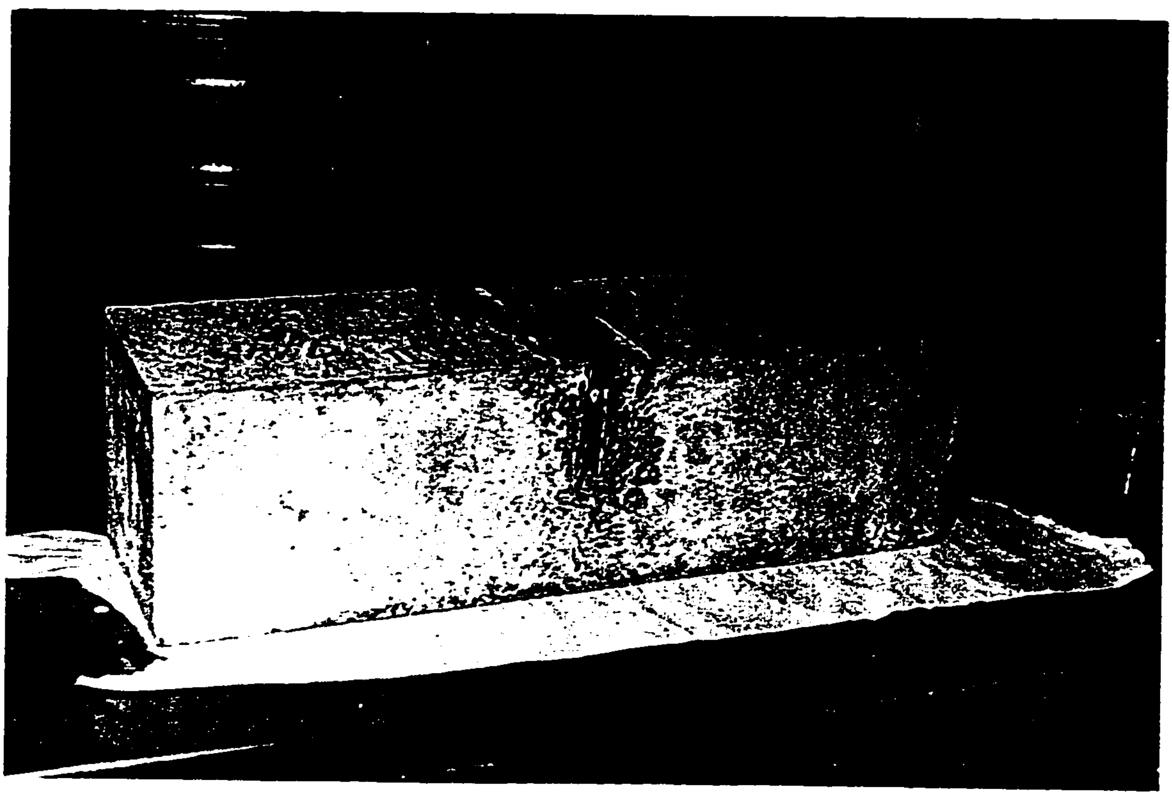


Plate 3.9: A beam specimen after removing the sealant at the end of the curing time of epoxy compound.

affected.

3.4.2 *Repair of Cylindrical Specimens*

Similar procedure was taken in the repair of cylinders with the exceptions mentioned below:

1) Surface Preparation: The slant surfaces of the half cylinders were sand-blasted instead of using the thin saw blade and emery cloth. Limited duration of sand-blasting would roughen the concrete surface and remove any latent materials that were associated with a fair face concrete surface.

2) Sealing the Crack Surface: In order to fix the two half cylinders together to form a cylinder with a gap of thickness running in an inclined direction of 30^0 from the vertical, the sealing process of cylinder was made in two stages. In the first stage one half was put on top of another and held in position by tightening a steel ring of 12.5 mm (1/2 in) width around the two halves at the middle of height of the cylinder. Two metal strips of thickness 1.6 mm (1/16 in) were placed between the two halves above and below the ring to keep the gap required between the two halves. After hard adjustments to get the two halves aligned forming a cylinder with a gap, the ring was tightened properly and the sealing material was applied to small intervals at the top and bottom of the crack boundaries (Plate 3.10).

On the next day and after curing of these portions, the ring and metal strips were removed, the 'crack' was cleaned by air pressure, entry and exit nipples were fixed, and the rest of the crack boundary was sealed completely (Plate 3.11).

3) Epoxy Injection: Sealing and injection of each group of cylinders with the three types of epoxy were made after at least 22 days from the end of the water curing due to performing other activities in that period of time. After injecting the epoxy, lower and upper nipples were capped and cylinders were left for curing for at least 4 days.

4) Removal of the Sealant: Finally, the sealant was removed in a similar manner using the hand grinder and a vice for the fixation of the cylinder during work.

All cylinders were treated in the same manner during their repair by the three types of epoxies used.

3.5 Exposure to Simulated Severe Environmental Conditions

3.5.1 Conditioning Devices

(a) Brabender Humidity Chamber:

A Brabender humidity chamber was used in heating the beam specimens (Plate 3.14). Its temperature range is from 10°C upto 100°C (50°F upto 212°F) with accuracy ± 0.5°C (± 0.9°F). A wide

Plate 3.10: A group of cylinders after the first stage of the sealing process.

Plate 3.11: A group of cylinders after completing the sealing process.

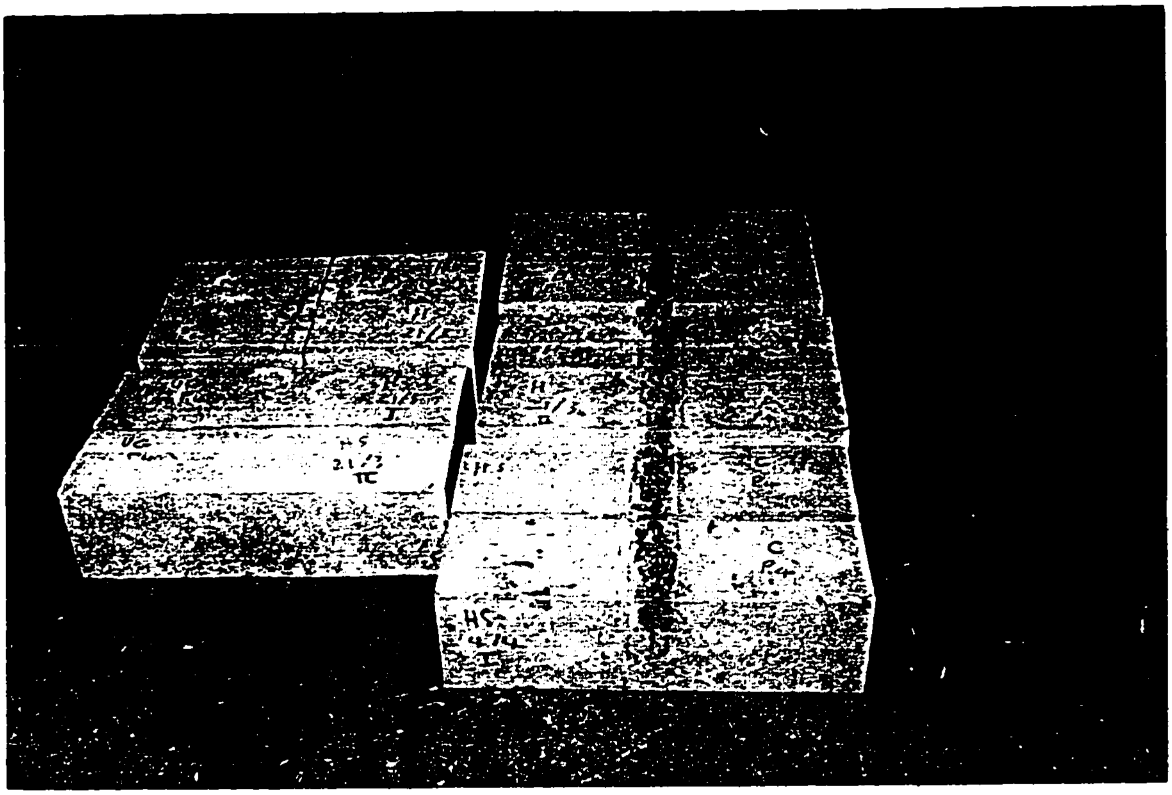


Plate 3.12: A group of repaired and reference beam specimens ready for heat-cool cycling.

Plate 3.13: A group of repaired and reference cylinder specimens ready for heat-cool cycling.

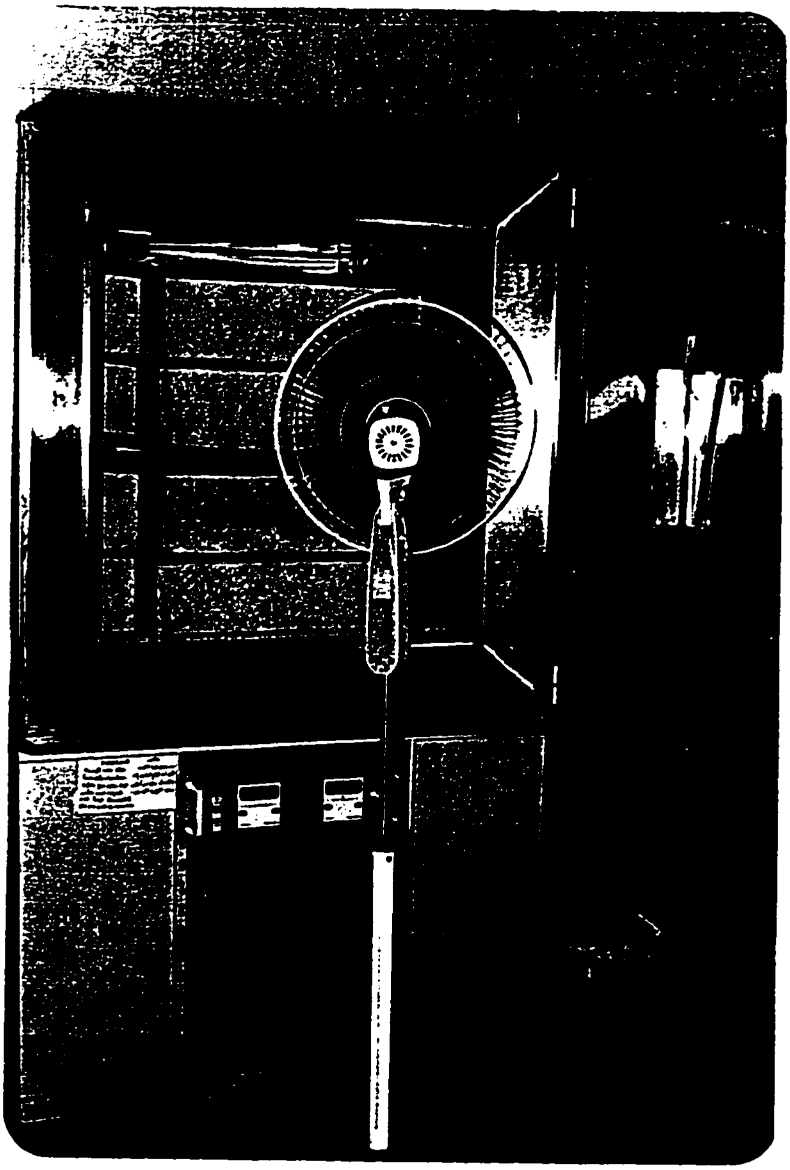


Plate 3.14: Heat-cool cycling of beam specimens.

range of 10% upto 95% relative humidity with an accuracy of ± 3% relative humidity could be obtained with the working temperature applied. It has a large working space for specimens under investigation.

(b) Memert Oven:

A Memert oven was used in heating the cylindrical specimens (Plate 3.15). Its temperature range is from 50°C, upto 220°C (122°F upto 428°F) with a control knob for the amount of fresh air entry. The maximum fresh air entry is obtained at position 6 although this does not signify a complete change of air within the chamber. The recommended maximum load of specimens for homogeneous temperature distribution in the working chamber is 30 kg (66.2 lb).

3.5.2 Hot Environment Condition

(a) Beams:

A group of ten beams, 2 beams repaired by each type of epoxy after curing, 2 beams grooved unrepaired, and 2 beams ungrooved, with thermocouple wires embeded into them (in concrete and epoxy) were placed in the humidity chamber. The chamber was adjusted at (70°C) 158°F and 35% relative humidity and set on for a period of 6 hours. The core temperatures of concrete and epoxy of each beam were measured immediately after taking it from the chamber using the thermocouple meter and then it was tested in flexure directly with the groove area being under tensile flexural stresses. After failure

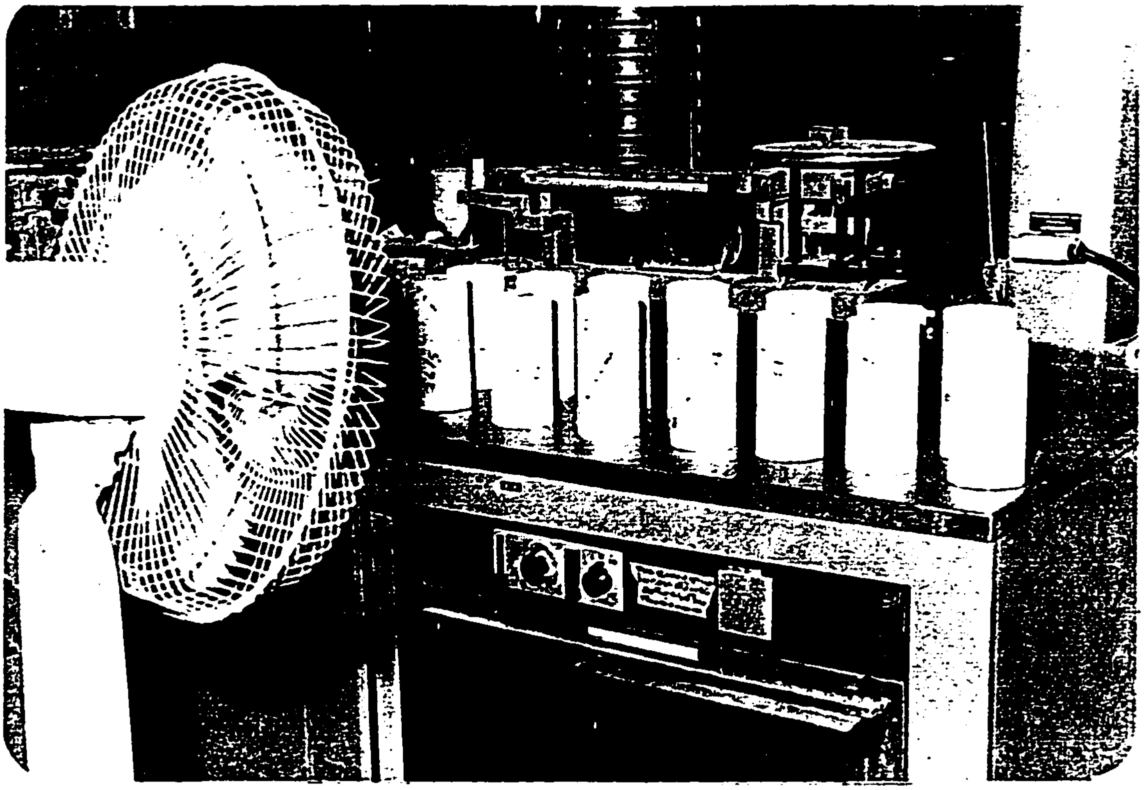


Plate 3.15: Heat-cool cycling of cylinder specimens.

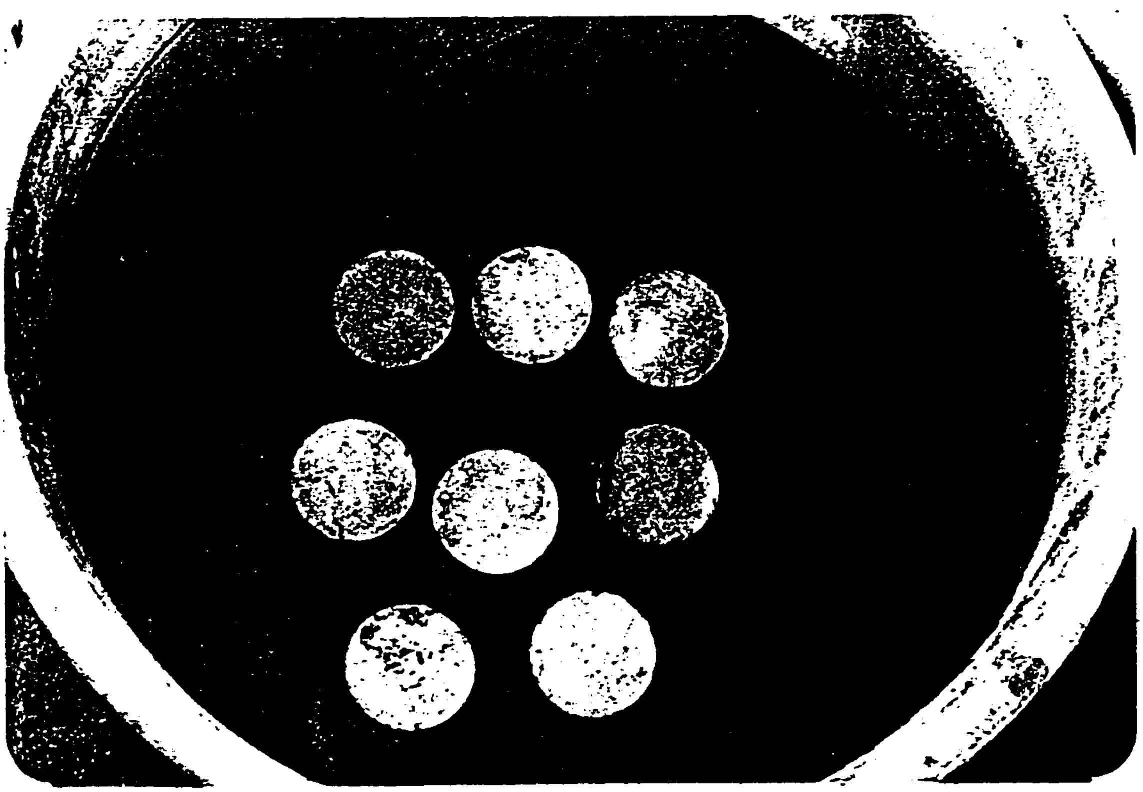


Plate 3.16: A group of cylinders immersed in water during the wet-dry cycling process.

the core temperatures were measured again so that an average temperature of the beam during the test could be obtained. Another group of beams was tested under normal conditions. i.e. at room temperature (20°C = 68°F) and without heating or cycling in order to form reference values for the results of other groups of beams tested under other conditions.

(b) Cylinders:

A group of eight cylinders, 2 cylinders injected by each type of epoxy and two complete ones, with thermocouples embeded into them (in concrete and epoxy also) were placed in the oven, which was adjusted at 70°C (158°F) with maximum ventilation and set on for a period of 6 hours. Temperature readings of the cores of cylinders were measured immediately after taking each cylinder out of the oven for testing in compression. Temperature readings were taken again after the test and average values were calculated for the temperature of cylinders during the tests. Similar to beams, another group of cylinders was tested at room temperature (20°C = 68°F) and without heating or cycling in order to form reference values for the results of other groups of cylinders.

3.5.3 Heat-Cool Cycling Program

(a) Beams:

Four groups of beam specimens, each of which consisted of 2 beams repaired by each type of epoxy, 2 grooved unrepaired beams and two complete ungrooved ones (Plate 3.12), were exposed to 0, 50, 100 and 150 heat-cool cycles, one group for each specific number of cycles. The first group of 0 (H/C) cycles was not exposed to any heat-cool cycles and it was actually the same group which was tested at room temperature (20°C = 68°F), and which was mentioned in Section 3.5.2. The humidity chamber was adjusted at (70°C) 158°F and 35% relative humidity and beams ready for cycling were inserted into it. In each heat-cool cycle the chamber was set on for a period of 6 hours, and then it was set off, its door was open, and an electric fan placed in front of the beams was put on for another 6 hours to get the temperature of the beams back to room temperature (20°C = 68°F) (Plate 3.14). During this cycle the core temperature of beams was increased gradually upto about 65°C ± 3°C (140°F ± 5.4°F), and then decreased to room temperature. Beams were arranged systematically in the chamber with each two beams of the same characteristics on top of each other and 2 cycles could be performed daily. After completing the number of cycles specified, beams were taken out of the oven and left for at least three days, after which they were tested while they were cool.

(b) Cylinders:

Similar to beams, four groups of cylinders, each group consisted of eight cylinders: 2 cylinders repaired by each of the three types of epoxy and 2 complete reference ones (Plate 3.13), were exposed to 0, 100, 200 and 316 heat-cool cycles, one group for each specified number of (H/C) cycles. The group of cylinders of 0 H/C cycles was actually the same group which was tested at room temperature (20°C = 68°F), and which was mentioned in Section 3.5.2. The number of cycles was increased since early results showed that more cycles were needed to reflect the adverse effect of cycling in this case. During the heat-cool cycles, cylinders were placed inside the oven, which was adjusted at 70°C (158°F) and maximum ventilation for a period of 6 hours, where their temperature rose gradually upto about 65°C ± 3°C (149°F ± 5.4°F), and then were taken out of the oven to cool down in front of an electric fan for another period of six hours (Plate 3.15). Two (H/C) cycles were performed daily, and few missed cycles were compensated for later. At the end of the specified number of cycles cylinders were tested seven days later, at least, in compression while they were cool.

3.5.4 Wet-Dry Cycling Program

(a) Cylinders:

Another three groups of cylinders of eight cylinders each, 2 cylinders repaired by each type of epoxy and 2 complete ones, were given 0, 80, and 120 wet-dry cycles, one group for each specified number of cycles (the group of cylinders of 0 W/D cycles was actually the same group of 0 H/C cycles and 20°C = 68°F test temperature). Each wet-dry cycle consisted of putting the cylinders in water for 12 hours, followed by putting them in the oven at 70°C (158°F) for six hours, and finally putting them in front of an electric fan for 6 hours (Plates 3.16, 3.15). One cycle was performed daily and at the end of the specified number of cycles cylinders were tested in compression at least seven days later.

3.6 Testing of Beams and Cylinders

3.6.1 Testing of Beams

Concrete beams were tested in flexure with third-point loading according to ASTM C78-84 standard test method [42] (see Fig. 3.2). A bond testing device of 200 kN maximum load, accuracy: class 2 DIN 51220/Grade B BS 1610, and attached to Automatic Compression Testing Machine "TONIPACT 3000" was used for testing the concrete beams in flexure. The speed rate of loading was adjusted at 0.28 kN/S (3.78 kips/min) and the breakage (ultimate) load was recorded in the digital display. After beams were prepared for testing, they were positioned on the machine so that the repaired and unrepaired grooves were on the tension side with the load applied downwards at the two third points of the beam span. A linear variable differential transducer (LVDT) device was placed at the center of the beam from underneath to measure the center point deflection. A TML portable data logger (TDS-301) was connected to both the Tonipact machine and the LVDT device for recording the reading of applied load and central deflection each 5 kN interval as desired (Plate 3.17). In the case of beams tested while hot, the temperature for each specimen

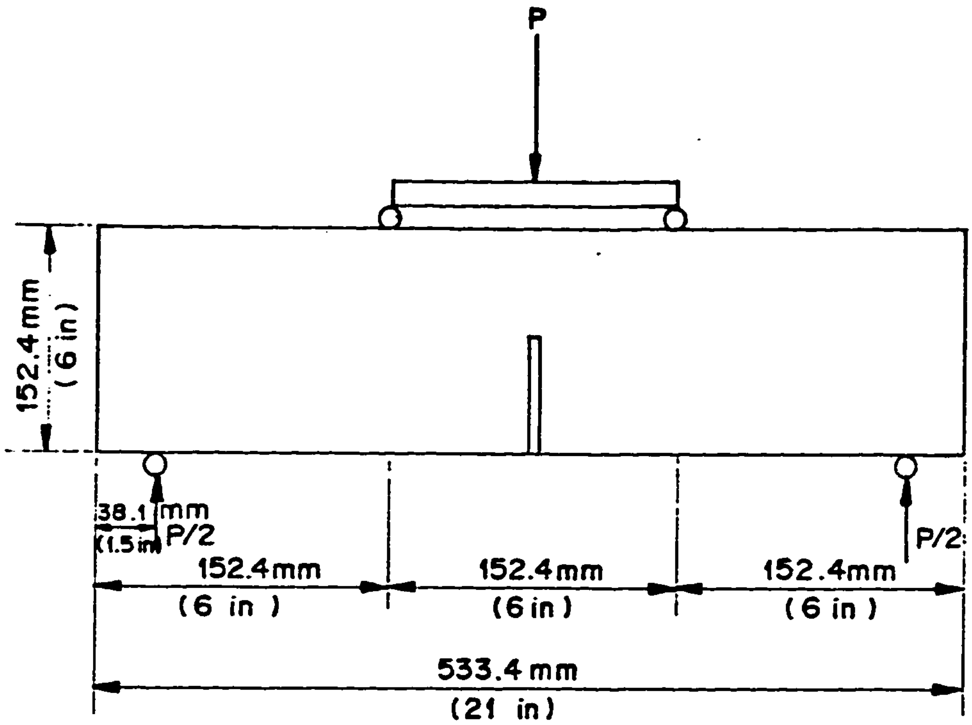


Fig. 3.2: Third Point Loading Flexural Strength Test of Beam Specimens

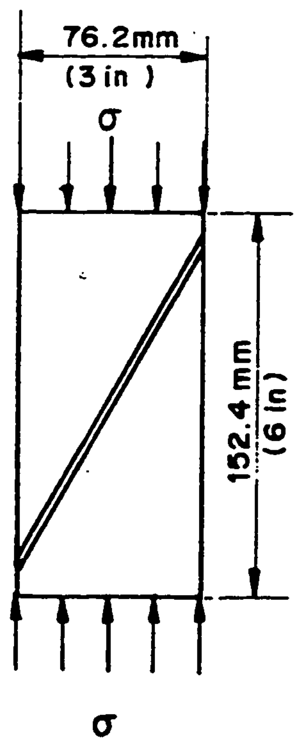


Fig. 3.3: Compressive Strength Test of Cylindrical Specimens

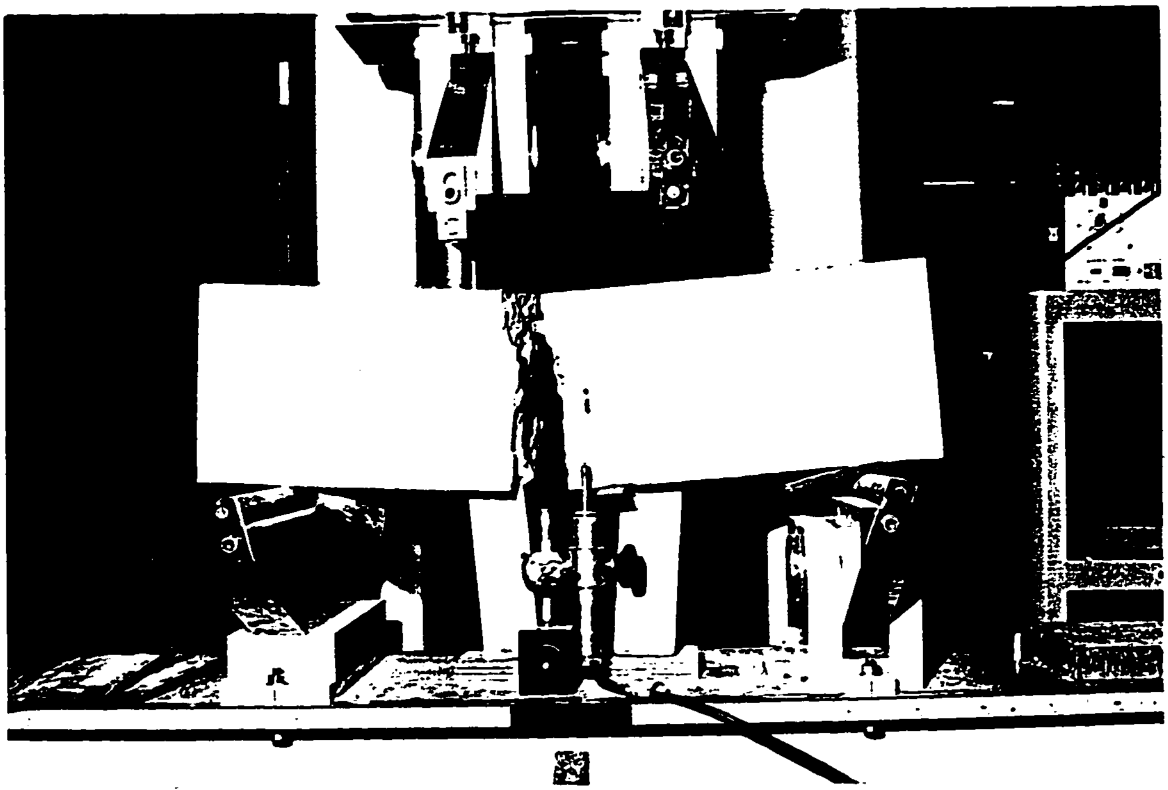


Plate 3.17: Failure of a beam specimen in flexure under third point loading test.

was measured just before and after the test as mentioned earlier.

3.6.2 Testing of Cylinders

ASTM C39-83b is a standard test method for compressive strength of cylindrical concrete specimens [43]. A Wykeham Farrance testing machine of model 55113 and capacity 1500 kN (337 kips) was used for testing the cylinders in compression. A Forney Universal Testing Machine of model LT-0950-DN and dual range {1780 kN, (400 kips) compression, 1780 kN (400 kips) tension} was also used for testing the group of hot cylinders immediately after taking them out from the oven and measuring their temperature. Cylinders were capped with sulphur compound from both sides for levelling them and tested in compression with a speed rate of about 2.5 kN/s (33.7 kips/min), and the ultimate load applied was recorded for each cylinder (Fig. 3.3). Hot cylinders temperatures were recorded just after the test also.

Chapter 4

ANALYSIS OF DATA & DISCUSSION OF RESULTS

4.1 General

This chapter is devoted to the presentation of data obtained from the experimental program of this study. Each set of experimental data is presented, manipulated and discussed in order to reflect on the salient objectives of these experiments. The experimental objectives and methodologies adopted for their achievement were presented in Chapters 2 and 3 respectively.

Results of the compressive strength of the concrete control specimens are presented first, so as to give an idea about out-of-group variations in concrete quality. This is followed by the experimental results of the different testing programs on beams and cylinders. Finally a comparison of the effects of the various factors on the performance of epoxy repaired beams and cylinders is presented.

4.2 Results of Concrete Quality Control Specimens

The concrete mix design for the various beams and cylinders used in this study was selected carefully and was unified throughout the casting program (see Section 3.3). Since it was not possible to cast all the beams and cylinders in a single casting, care has been exercised to divide these castings into groups, each group relating to the same experiment, so as to reduce the effects of out-of-group variations as much as possible. Extra care and precautions were taken to reduce these out-of-group variations to a minimum. This included attempts to cast each group at about the same ambient labo-ratory temperature followed by a unified sequence of finishing, cur-ing and handling of the various castings that contribute to the same experiments.

In all, nine castings were carried out for all the beams and cylinders (see Section 3.3). Three 75 mm (3 in) diameter concrete cylinders were obtained for each casting, so as to determine its com-pressive strength after a specific duration of 28 days. As mentioned earlier, the same curing, handling and storage conditions were applied to these castings as strictly as possible. Results of compres-sive strength tests on these control specimens are presented in Table 4.1 and illustrated in Fig. 4.1.

The average compressive strength for these nine mixes is 40.0 MPa (5800 psi) with a standard deviation of 4.4 MPa (640 psi). The coefficient of variation equals 11%. These values are within the ball mark figures expected for out-of-group concrete variations.

In general, variations in the strength of concrete test speci-mens depend on how well the materials, concrete manufacture, and testing are controlled. Variations in strength can be traced to two fundamentally different sources: (a) differences in

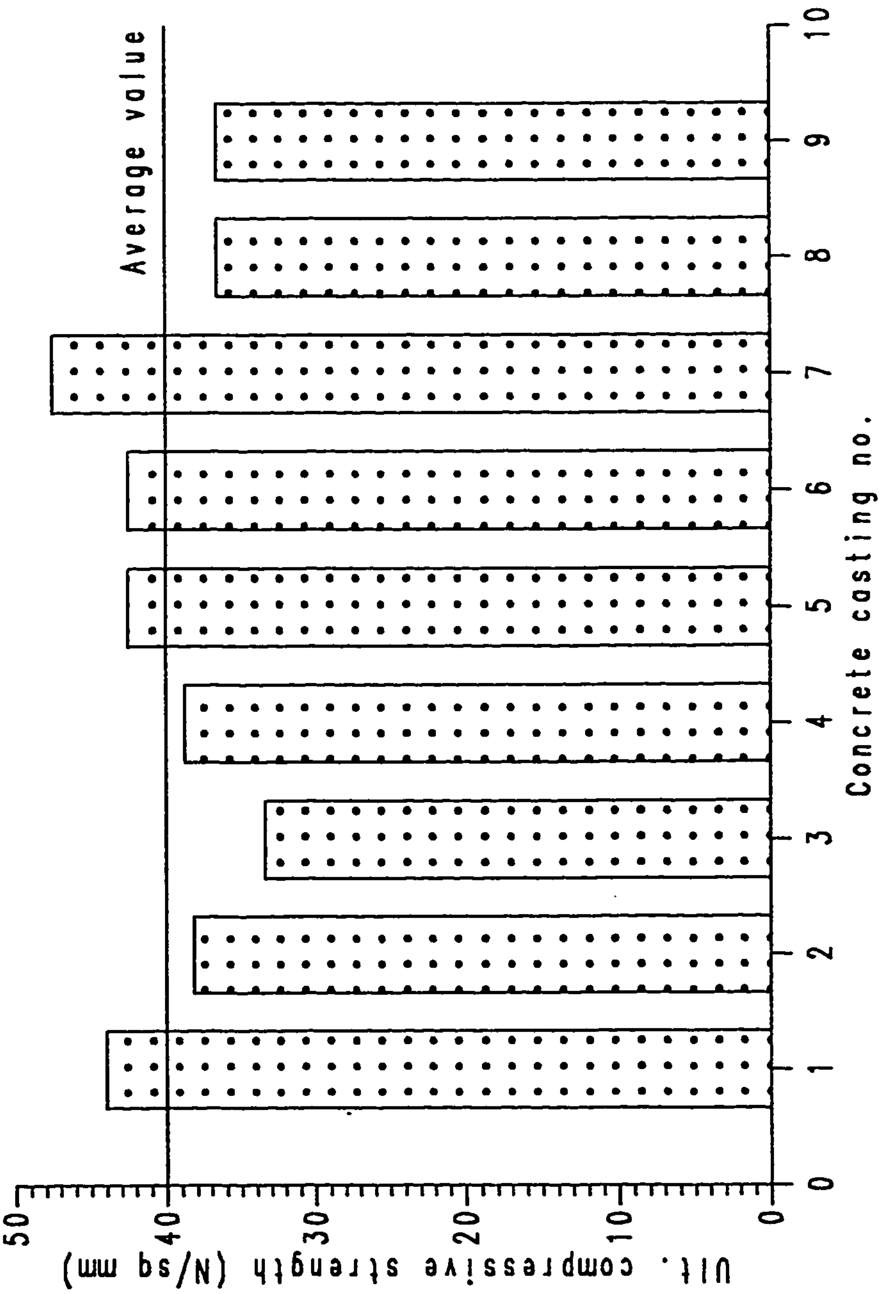
Table 4.1: Data for Concrete Quality Control (Overall Average Ultimate Compressive Strength = 40.0 N/mm^2 (5800) psi with Standard Deviation = 4.4 N/mm^2 (640) psi and Coefficient of variation = 11%)

Concrete Casting #	Average Compression Strength(psi)	Purpose
1	44.0 (6380)	10 beams for 150 H/C, 8 cylinders for 120 W/D
2	38.2 (5540)	10 beams for 100 H/C, 8 cylinders for 80 W/D
3	33.4 (4840)	10 beams for 0 H/C and 20°C(68°F) 8 cylinders for 40 W/D
4	38.8 (5630)	10 beams for 50 H/C
5	42.5 (6160)	10 beams for 62°C (143.6°F) 8 cylinders for 63°C (145.4°F)
6	42.5 (6170)	8 cylinders for 200 H/C
7	47.5 (6890)	8 cylinders for 100 H/C
8	36.6 (5300)	8 cylinders for 316 H/C
9	36.6 (5300)	8 cylinders for 0 H/C and 0 W/D and 20°C(68°F)

Key:

H/C : Heat-Cool Cycles
W/D : Wet-Dry Cycles

FIG. 4.1: Concret Quality Control Chart
Av. fc(ult)=40.0 N/sq mm (5800 psi)
(with St. Deviation = 4.4 N • Coef. of Variation = 11%)



strength-producing properties of the concrete mixture and ingredients, and (b) apparent differences in strength caused by variations inherent in the testing (44). Among these factors, the use of cement from different sources, or even the use of different batches of cement from one work, leads to an appreciable variation in the strength of concrete (45).

The variation in strength test results of the nine castings in one work could be mainly attributed to the variation in strength of Type I cement used with addition to the slight variations in the mixing, placing, and curing procedures.

4.3 Results of Testing at High Temperature

4.3.1 Strength of Repaired Beams Tested While Hot

It was aimed to examine the effect of high temperature exposure on the performance of epoxy repaired beams with the three types of epoxies used and on the bond between epoxy and concrete when subjected to linear tensile stresses resulting from loading the beam specimens in flexure. A group of beams (ten beams in total) was tested at 20°C (68°F), while another group of beams was heated for 6 hours in the oven, which was adjusted at 70°C (158°F) and 35% relative humidity, and then immediately tested while hot, at which the core temperature of the specimens was 62°C (143.6°F) (Fig. 3.2). The details of this experimental program was documented in Chapter

3, and the results of these tests are shown in Table 4.2 and presented graphically in Fig. 4.2.

Fig. 4.2 illustrates the clear reduction in flexural strength of the epoxy injected beams as their temperature rises beyond the laboratory ambient temperature of 20°C (68°F). To fully understand this phenomenon, one must first examine the beams designated S and G. These beams have no epoxy products and their variations should reflect the rise of temperature impact on the flexural strength of concrete beams. Both kinds of beams have shown a reduction in their flexural strength at higher temperature of 62°C (143.6°F). However, the reduction in the (S) beams flexural strength is more drastic than that of the (G) beams.

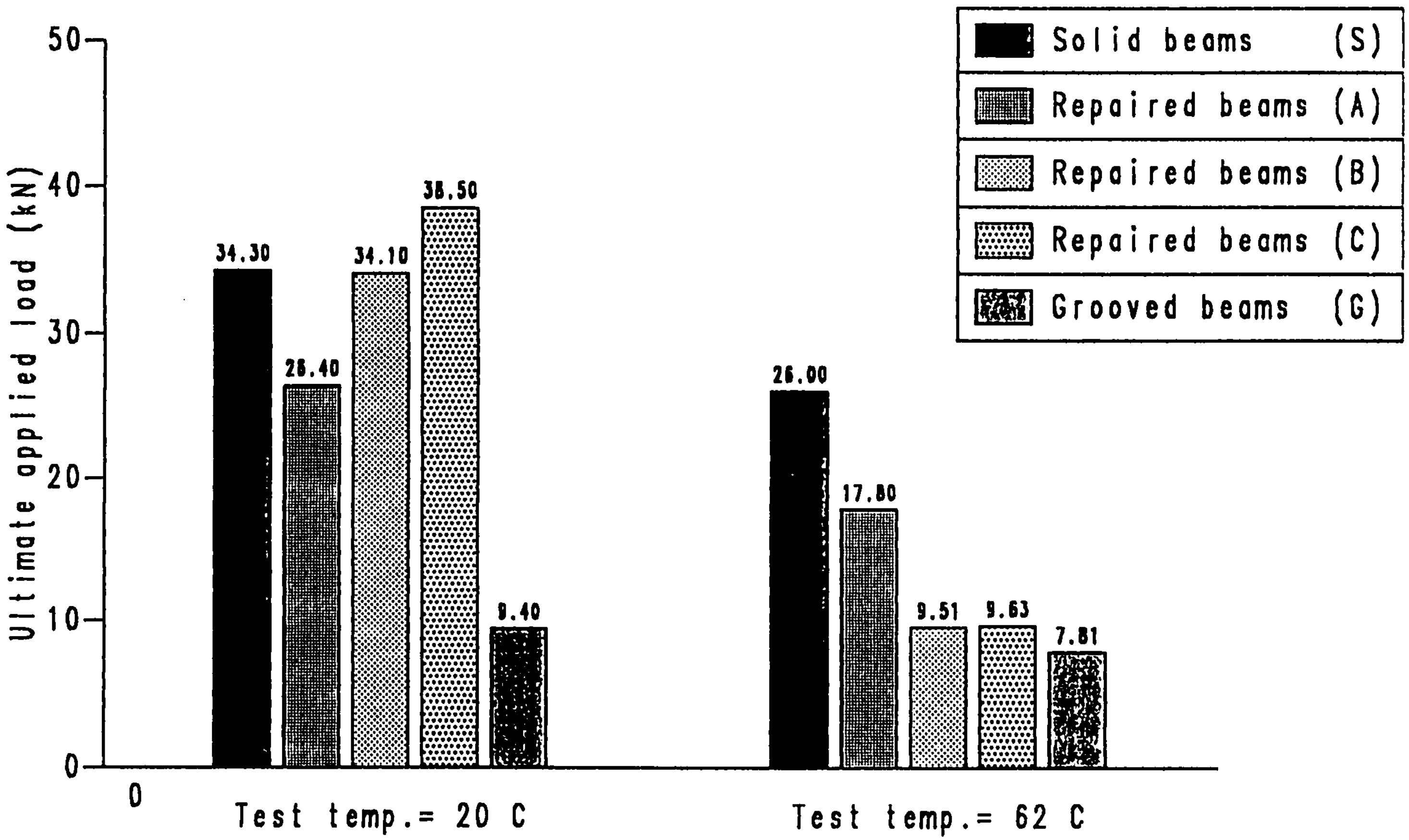
In literature, the effect of increase in temperature on the strength of concrete is small and somewhat irregular below 250°C (482°F), but above about 300°C (572°F) a definite loss of strength takes place. In addition, concrete flexural strength is known to be more sensitive to temperature variations than its compressive strength (45).

Since the rise in temperature is rather modest, we do not believe that the large reduction in the strength of the (S) beams can solely be attributed to the increase in temperature. A large portion of this reduction might be attributed to variations in the strength of concrete, as well as variations in the testing process (see Section 4.2).

Table 4.2: Effect of Temperature on Epoxy-Injected Repaired Beams

Type of Beam		Ultimate Applied Load(kN) @	
		20°C(68 F)	62°C(143.6°F)
Solid Uncracked	(S)	34.3	26.0
Cracked and Repaired with Epoxy A	(A)	26.4	17.8
Cracked and Repaired with Epoxy B	(B)	34.1	9.5
Cracked and Repaired with Epoxy C	(C)	38.5	9.6
Grooved (Cracked & Unrepaired	(G)	9.4	7.8

Fig. 4.2: Effect Of Temperature On the Fllexural Strngth of Epoxy-injected Repaired Beams



On the other hand, the reduction in strength for the (G) beams (of the order of 15%) is more representative of the expected reduction in flexural strength of concrete made of limestone aggregates when tested hot at about 65°C [46]. Therefore, using the (G) beams strength as a reference benchmark, one can turn now to the study of the effect of heat on the bond performance of the three epoxy products.

One possible way of examining the effect of heat on the bonding capacity of epoxies is to relate the extra gain in the flexural strength of the A, B and C beams beyond that of the (G) beams to the bonding contribution of epoxies. At room temperature of 20°C (68°F), the epoxy products are bringing the beams almost to the full strength of the solid uncracked (S) beams. This fact is manifested by the failure of concrete away from the bond line in specimens repaired with epoxy C and tested at 20°C (68°F). Even when failure occurs at the bond line, as has been the case for specimens repaired with epoxies B and C, traces of concrete could be seen attached to and covering the epoxy bonding layer. While at 62°C the epoxy treated beams (A, B and C) have only contributed very slightly to the flexural strength beyond that provided by the (G) beams.

To quantify the epoxy contribution to the flexural strength of beams at both temperature levels, one can evaluate the extra strength (kN) that epoxy beams have provided beyond that provided by the (G) beams. Such contribution is listed in Table 4.3 and

Table 4.3 Contribution of the Epoxy-Concrete Bond to the Ultimate Strength of Flexural Beams (kN)

Specimen Type	Test Temperature @	
	20°C(68 F)	62°C(143.6°F)
Cracked and Repaired with Epoxy A (A)	17.0	10.0
Cracked and Repaired with Epoxy B (B)	24.7	1.7
Cracked and Repaired with Epoxy C (C)	29.1	1.8

Table 4.4 Percentage Loss in Bond Flexural Capacity between Epoxy and Concrete in Beams due to Temperature Rise (in terms of the bond flexural capacity at 20°C)

Specimen Type	Test Temperature @	
	20°C(68 F)	62°C(143.6°F)
Cracked and Repaired with Epoxy A (A)	0	41.0
Cracked and Repaired with Epoxy B (B)	0	93.1
Cracked and Repaired with Epoxy C (C)	0	93.7

illustrated graphically in Fig. 4.3. This figure clearly shows the marked degradation in the contribution of the epoxy bond strength to the flexural strength of epoxy repaired beams. From Fig. 4.3, a percentage loss of the bonding capacity for each of the three epoxy products can be evaluated as:

$$\% \text{ loss} = \frac{P_{20} - P_{62}}{P_{20}} \times 100$$

where:

P_{20} = Flexural strength contribution of the epoxy product at 20°C (68°F)

P_{62} = Flexural strength contribution of the epoxy product at 62°C (143.6°F).

Graphic presentation of this percentage loss of bond at higher temperature is shown in Table 4.4 and Fig. 4.4. Product A lost some 40% of its bond contribution to the flexural strength of repaired beams, while products B and C have lost over 90% of their contribution when their temperature was elevated to 62°C (143.6°F). It is worth mentioning that the failure pattern of the repaired beams at the 62°C (143.6°F) temperature was by the debonding of the epoxy layer from one of the crack faces, with no traces of concrete to the epoxy. In fact the epoxy itself was in a cheesey or rubbery form and could be peeled off from the concrete quite easily.

In literature, Fattuhi [23] examined the effect of temperature on

Fig. 4.3: Effect of Temperature on the Contribution of the Epoxy-concrete Bond to the Ultimate Flexural Strength of Beams

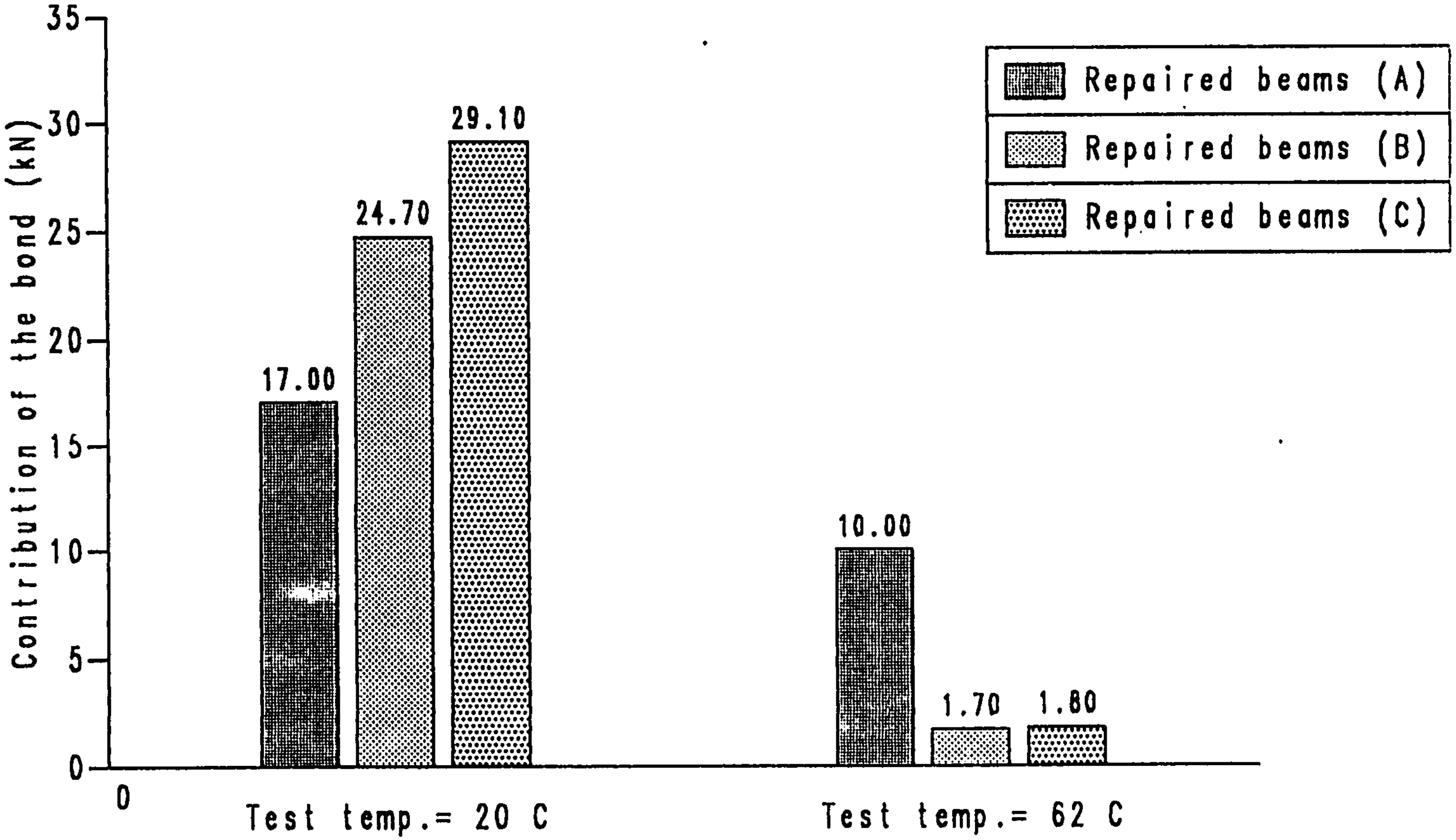
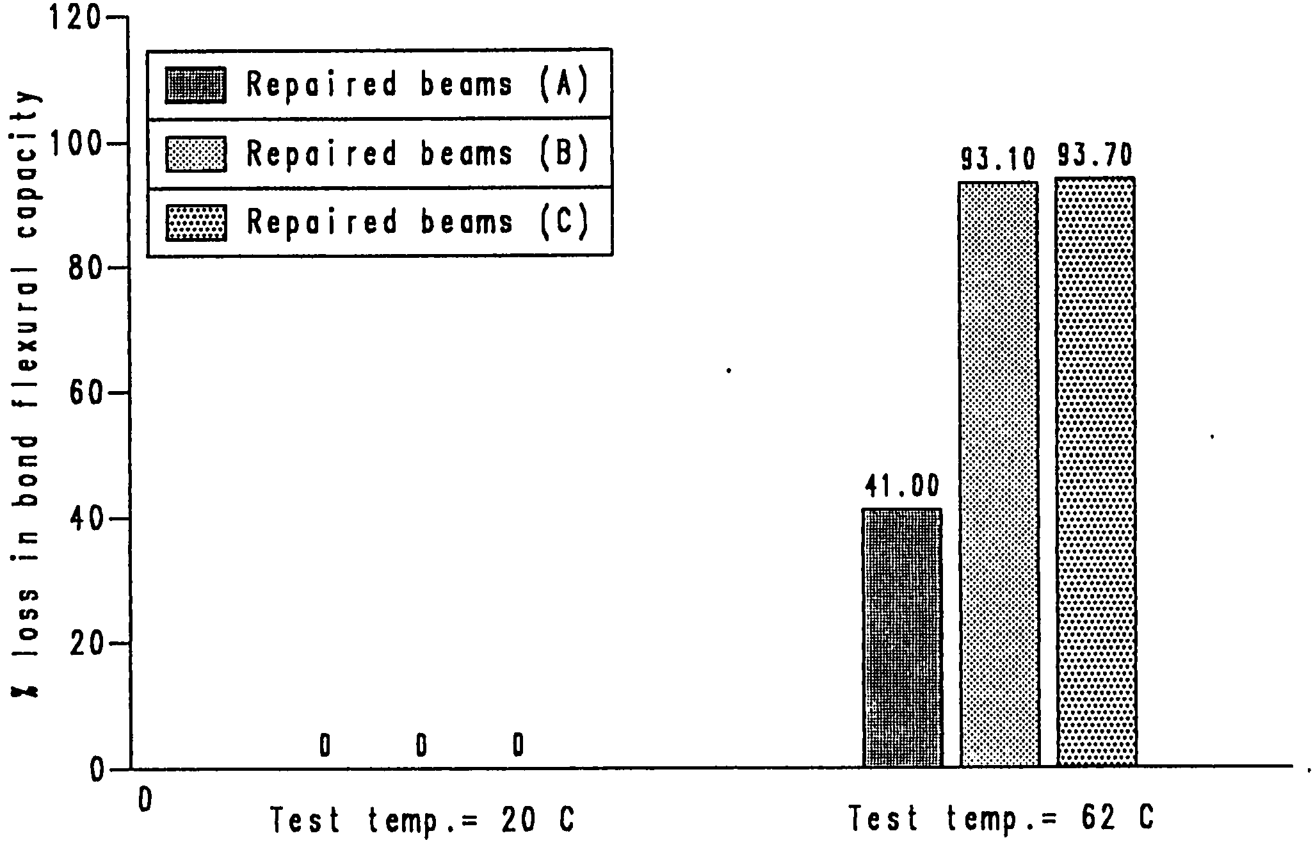


Fig. 4.4: % Lossin Bond Flexural Capacity between Epoxy and Concrete due to Temp. Rise (in terms ofthe Bond Flex.Capacity @ 20C)



the flexural strength of similar beam specimens repaired with three different adhesives [see Section 2.1.4(3)]. He reported nearly 50% reduction in the strength of those beams repaired by an epoxy resin grout adhesive when tested at 63°C (145°F), where the failure occured at the repair section through the adhesive.

4.3.2 Strength of Repaired Cylinders Tested While Hot

The tests on repaired beams tested while hot reflected on the bond performance of the epoxy products when subjected to tensile stresses. These linear tensile stresses were the direct outcome of the flexural loadings imposed on the beams. To understand the bonding behavior under stresses other than the tensile ones, the slant shear test on repaired cylinders was used. In this test the repaired cylinders were loaded in compression (Fig. 3.3), where the bond between epoxy and concrete was subjected to combined compressive and shear stresses.

Two groups of full and half cylinders were casted, cured and repaired by the three epoxy products A, B and C. One group of these cylinders was tested at room temperature (20°C = 68°F) while the second group of cylinders was heated in an oven set at 70°C (159°F) for 6 hours and then tested immediately while hot. The embedded thermocouples in the cylinders recorded 63°C (145.4°F) at the time of the compression test. Results of these tests are listed in Table 4.5 and shown graphically in Fig. 4.5.

Several interactive phenomena can be realized by careful examination of the data presented in Fig. 4.5, among which are the following:

A) All repaired cylinders with epoxies A and C showed a reasonably high compressive strength at 20°C (68°F). These specimens produced an average strength around 80% of that of solid unrepaired cylinders (S). Their failure pattern was comparable to that of the solid cylinders, i.e. a failure characterized by the crushing of concrete in the middle zone, leaving the well recognized end cones.

Cylinders repaired by the product B have, on the other hand, failed by the shear failure manifested by the sliding of the two glued halves against each other. These cylinders could only attain about 45% of the strength attained by the solid (S) cylinders. This low performance could be related to an experimental error during the mixing and application of epoxy B to the cylinders or due to the fact that cylinders tested at room conditions were epoxy injected using epoxy B after a long period of time since the first time the cans of the two components of epoxy B were opened. This is explained in more details in Section 4.4.2. Cylinders repaired with epoxy B and tested while hot were epoxy injected using a new package of epoxy B components.

B) The solid concrete cylinders tested at 63°C (145.4°F) have

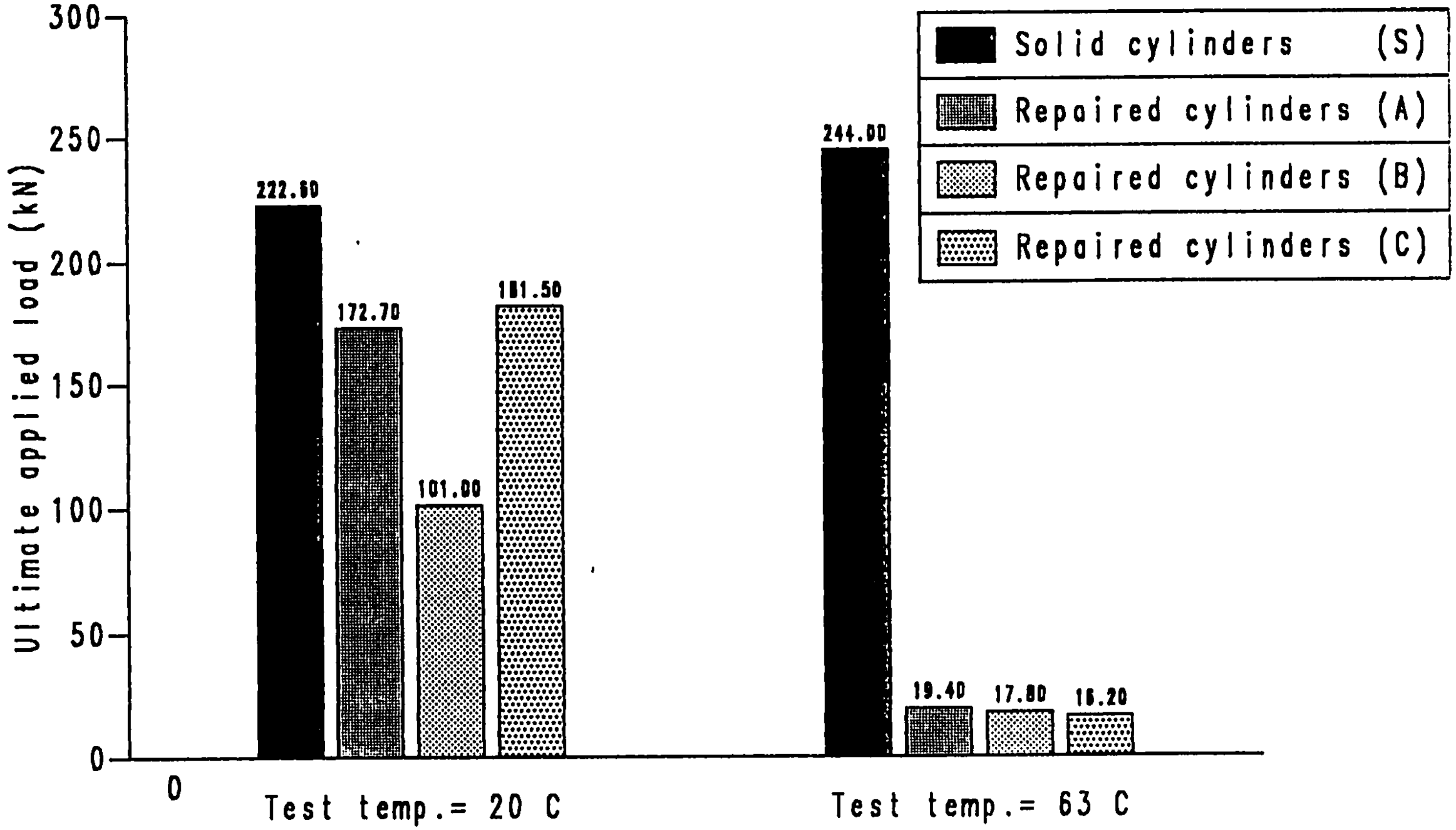
Table 4.5: Effect of Temperature on the Compressive Strength of Epoxy-Injected Repaired Cylinders

Type of Cylinder		Ultimate Applied Load(kN) @	
		20°C(68 F)	63°C(145.4°F)
Solid Uncracked	(S)	222.6	244.0
Cracked and Repaired with Epoxy A	(A)	172.6	19.4
Cracked and Repaired with Epoxy B	(B)	101.0	17.8
Cracked and Repaired with Epoxy C	(C)	181.5	16.2

Table 4.6: Effect of Temperature on the Compressive Strength of Epoxy-Injected Repaired Cylinders (as Percentage of S Value)

Type of Cylinder		Ultimate Applied Load (%) @	
		20°C(68°F)	63°C(145.4°F)
Solid Uncracked	(S)	100.0	100.0
Cracked and Repaired with Epoxy A	(A)	77.6	8.0
Cracked and Repaired with Epoxy B	(B)	45.4	7.3
Cracked and Repaired with Epoxy C	(C)	81.5	6.6

Fig. 4.5: Effect of Temperature on the compressive Strength of Epoxy-injected Repaired Cylinders



produced an average compressive strength of about 53.5 MPa (7760 psi). This represents about 10% increase over the strength of the cylinders tested at 20°C (68°F). The control cylinders for the two mixes from which the groups were made showed about 16% increase in the original 28 days strength of concrete used for casting the cylinders tested while hot in comparison to that used for casting the cylinders tested at room temperature (Table 4.1). Thus it appears that the net increase in the strength of solid concrete cylinders at 63°C (145.4°F) is the resultant of the effect of out-of-group strength variation of concrete used together with the effect of temperature on the strength of concrete.

C) Further study of Fig. 4.5 reveals that the concrete cylinders repaired by the three epoxy products have completely lost their bonding strength when tested hot at 63°C (145.4°F). Their failure pattern is characterized by the smooth sliding of one cylinder half against the other. The epoxy product behaved in a rubber-like material between the sliding concrete surfaces. This behavior confirms the early findings of the repaired beams tested in failure.

To further illustrate this drastic change of behavior of the three epoxy products, the strength of each repaired cylinder (A, B and C) is recorded as a percentage of that of the solid unrepaired cylinder (S) at the respective test temperature. Table 4.6 and Fig. 4.6 show such comparison.

From Fig. 4.6 a percentage loss of the bonding capacity under combined compressive stresses for each of the three epoxy products can be evaluated in terms of the ultimate applied load to repaired cylinders at room temperature (20°C = 68°F) as follows:

$$\% \text{ loss in bond} = \frac{P_{20} - P_{63}}{P_{20}} \times 100$$

where:

P_{20} = Ultimate applied load of repaired cylinders at 20°C (68°F) as a percentage of the solid cylinder values at 20°C (68°F).

P_{63} = Ultimate applied load of repaired cylinders at 63°C (145.4°F) as a percentage of the solid cylinder values at 63°C (145.4°F).

This is presented in Table 4.7 and Fig. 4.7. The average loss in bond performance for the three epoxy products when the epoxy-concrete bond was subjected to combined compressive and shear stresses is 89% when they were tested at 63°C (145.4°F).

Considering the average performance of repaired beams, we find that while the three epoxy products produced strengths in the vicinity of 80% of the solid concrete cylinders at room temperature (20°C = 68°F) (excluding results of cylinders of epoxy B at 0 H/C cycles), those same products could only produce about 10% of the

Fig 4.6: Effect of Temperature on the Compressive Strength of Epoxy-injected Repaired Cylinders (as percentage of (S) value)

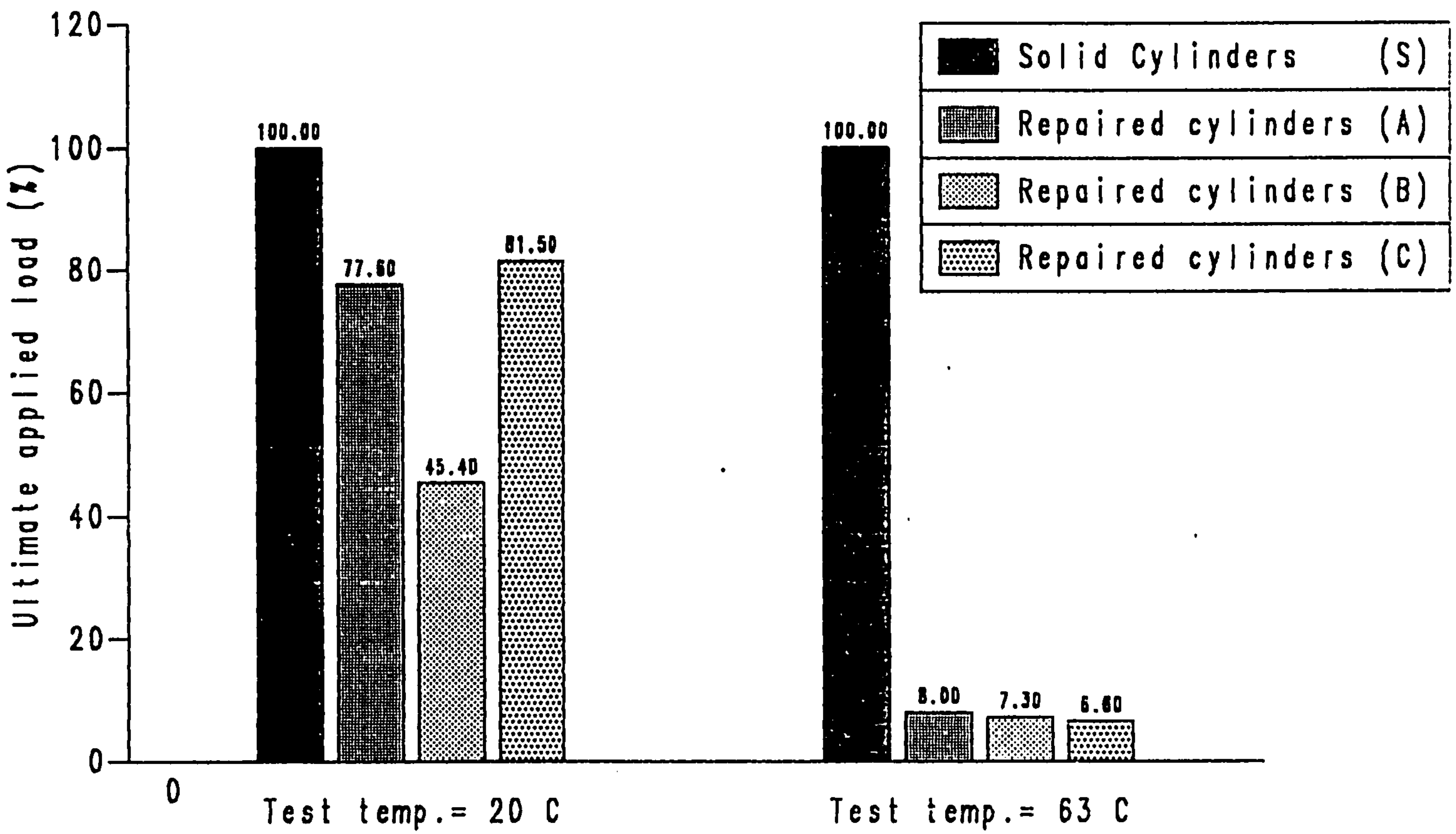
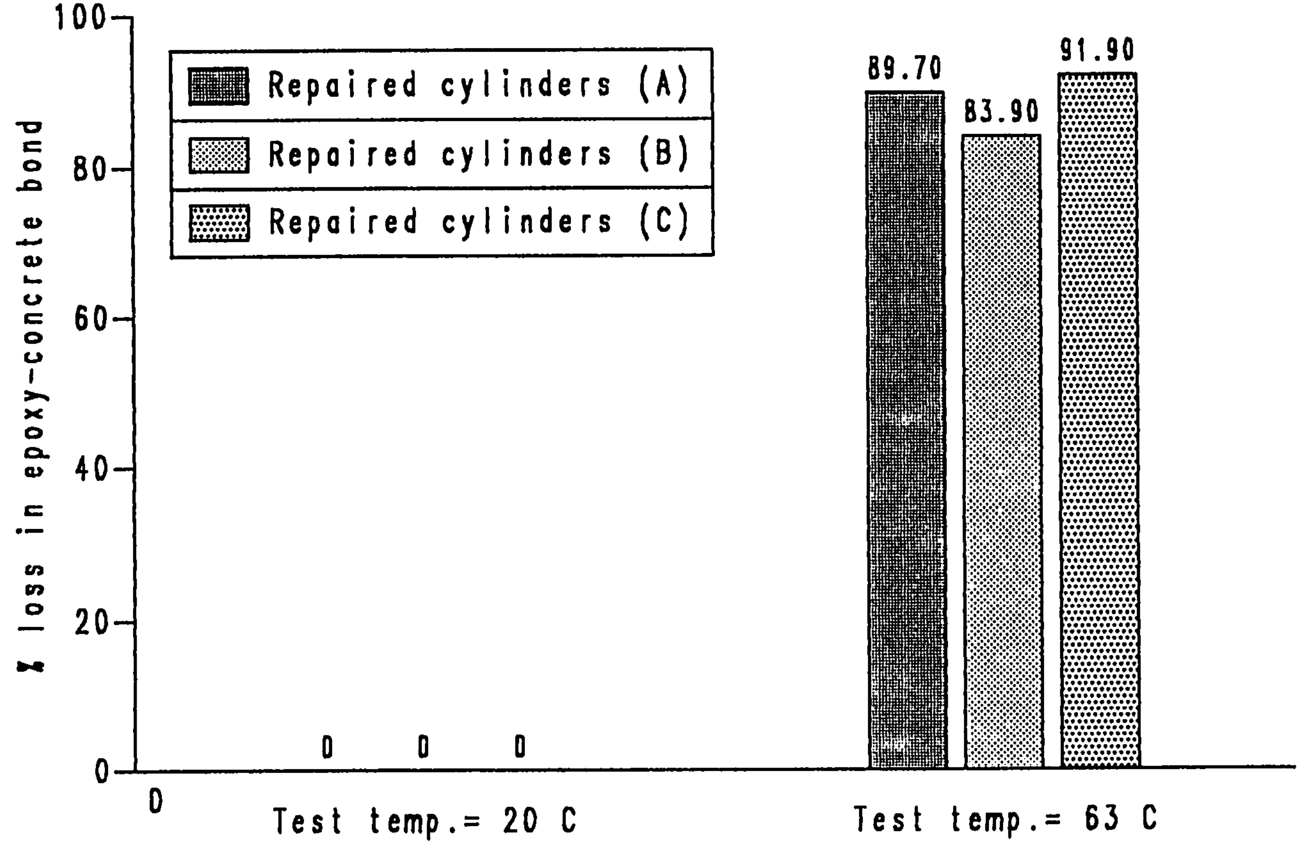


Table 4.7 Percentage Loss in Epoxy-Concrete Bond under Combined Shear and Compressive Stresses in Cylinders due to Applied Temperature of 63 C (145.4°F) (in terms of bond capacity at 20°C = 68°F).

Specimen Type	Test Temperature @	
	20°C(68 F)	63°C(145.4°F)
Cracked and Repaired with Epoxy A (A)	0	89.7
Cracked and Repaired with Epoxy B (B)	0	83.9
Cracked and Repaired with Epoxy C (C)	0	91.9

Fig. 4.7: % Lossin Bond under Combined Shear and Compressive Stresses due to Temperature Rise (in terms of Bond Capacity @ 20 C)



solid concrete cylinder strengths at 63°C (145.4°F). This statement is clearly noted in Fig. 4.8.

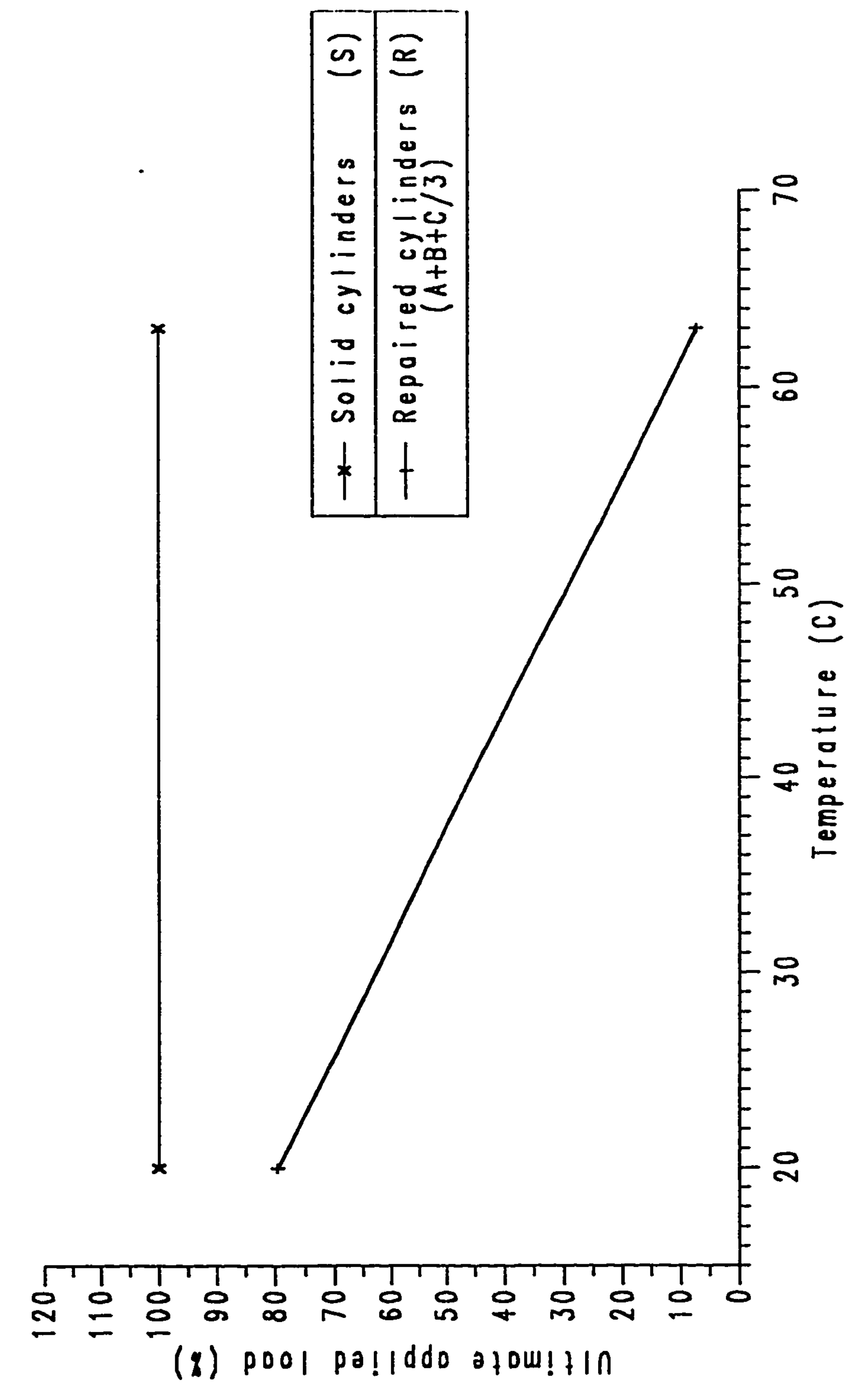
In summary, we can deduce from the results of repaired beams and cylinders that although these epoxy products A, B and C are functioning well at room temperature (20°C = 68°F), they lose most of their bond strength at temperatures as high as (62.5°C = 144.5°F), regardless whether the epoxy line is subjected to tensile or combined shear and compressive stresses. This behavior is believed to be due to the softening of these epoxies and the changes in their properties at this high temperature in addition to the development of high thermal stresses at the bond interface due to the difference between the coefficient of thermal expansion of each epoxy and that of concrete.

4.4 Results of Heat-Cool Cycling Program

4.4.1 Heat-Cool Cycling of Epoxy-Injected Beams

As explained in Chapter 3, four groups of beam specimens were exposed to 0, 50, 100 and 150 heat-cool cycles, and then tested while cool in flexure after at least three days from the end of the heat-cool cycling process (the group of 0 H/C cycles is actually the same group of beams which was tested at 20°C = 68°F and which was mentioned in Section 4.3.1). Each group of beams consisted of ten beams: 2 solid ungrooved reference beams, six grooved and repaired beams with the three kinds of epoxies used (A, B and C), and two

Fig. 4.8: Effect of Temperature on the Compressive Strength of Repaired cylinders with the Three Epoxy Products



grooved but unrepaired ones. Each heat-cool cycle consisted of six hours duration in the humidity chamber set at 70°C (158°F) and 35% relative humidity and six hours duration at room temperature, 20°C (68°F) and it was found that the maximum temperature gained during the cycle was 65°C ± 3°C° (149°F ± 5.4°F). Flexural loading test at the third points was applied on the beams (Fig. 3.2) in order to examine the effect of heat-cool cycling on the strength of repaired beams, where the epoxy-concrete bond was subjected to linear tensile stresses resulting from the flexural loading applied on each beam. Results of these tests are shown in Table 4.8 and graphical presentations of these data are shown in Fig. 4.9.

Considering Fig. 4.9, several important observations are noted, among which are the following:

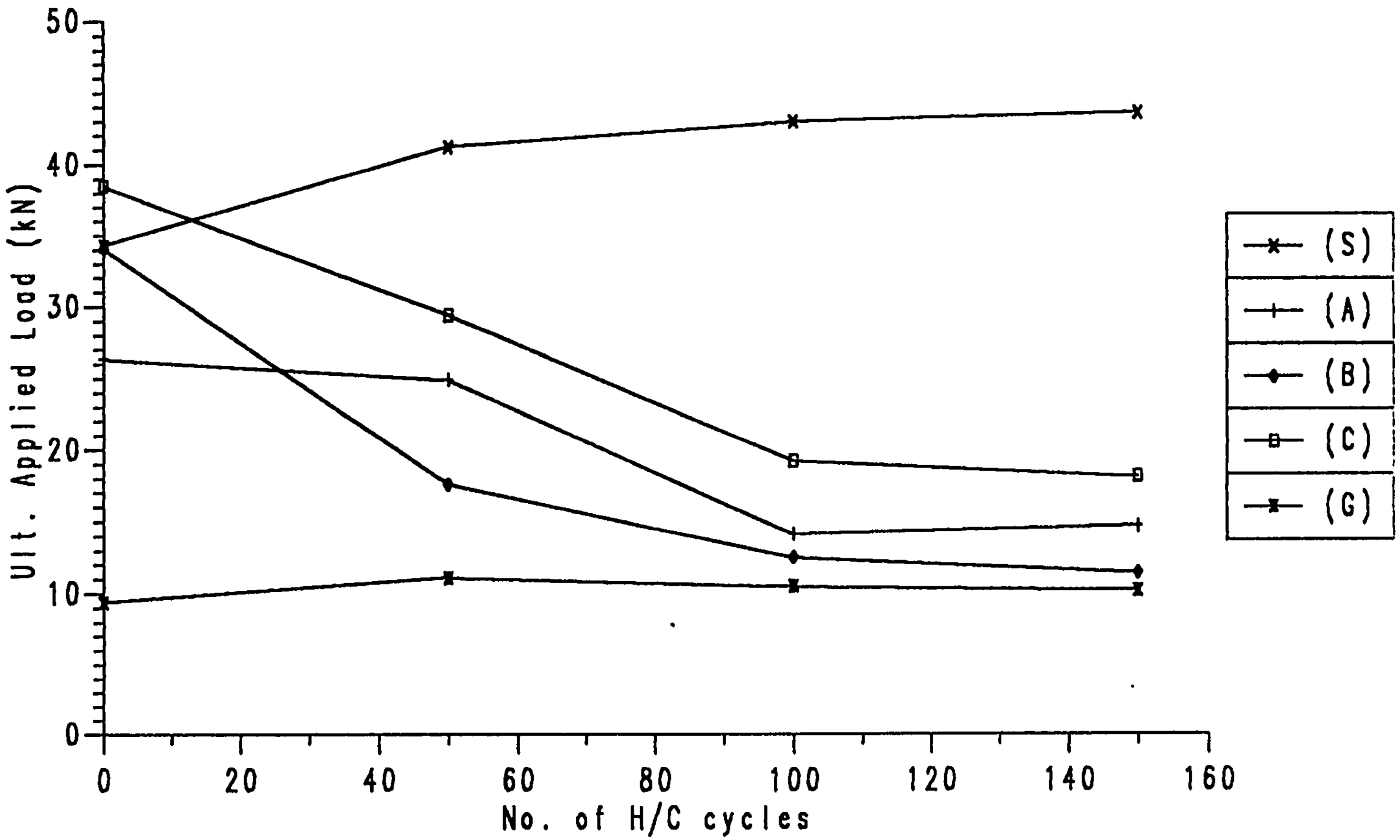
A) It is noted that the flexural strength of grooved unrepaired beams (G) represent about 25% of those of the solid ungrooved beams (S) at all of the four cycle marks (0, 50, 100, 150). This is well within our expectations, as the section modulus of the (G) beams at the groove section is exactly one-fourth of that of the (S) beams.

B) Both the solid (S) beams and the grooved unrepaired (G) beams exhibited about 20% marked increase in strength after 50 H/C cycles from that at 0 H/C cycles. Beyond 50 H/C cycles (i.e. 100, 150 H/C cycles) only very slight variation was noticed in the strength of these beams. This

Table 4.8: Effect of Heat-Cool Cycling on the Flexural Strength of Epoxy-Injected Repaired Beams.

Specimen Type	Ultimate Applied Load (kN)			
	0 H/C Cycles	50 H/C Cycles	100 H/C Cycles	150 H/C Cycles
Solid Ungrooved (S)	34.3	41.2	42.9	43.5
Grooved Repaired with epoxy A (A)	26.4	24.9	14.1	14.7
Grooved Repaired with epoxy B (B)	34.1	17.6	12.5	11.4
Grooved Repaired with epoxy C (C)	38.5	29.4	19.2	18.1
Grooved Unrepaired with epoxy (G)	9.4	11.1	10.5	10.2

Fig. 4.9: Effect of Heat-cool Cycling on the Flexural Strength of Epoxy-injected Repaired Beams



behaviour is mostly due to the following contributing factors:

i) It is known that concrete gains strength increasingly with time and the rate of gaining strength decreases as its age goes up [45]. Therefore it is expected that our specimens, which were having an age of about 40 days at the start of cycling process and which were tested during the first four months, were affected by this factor.

ii) When matured concrete is exposed to a higher temperature, it is expected that the rate of reaction of the remaining unhydrated cement will increase resulting in a faster gain of the remaining strength (45). On the other hand, repeating large changes in temperature would affect the strength of exposed concrete due to the development of thermal stresses between the cement paste and aggregates as a result of the difference in their coefficients of thermal expansion [47]. However, it is thought that beam specimens, which were exposed to the heat-cool cycling regime, were affected slightly by those factors since the maximum temperature reached ($62^{\circ}C = 143.6^{\circ}F$) and the nature of the heat-cool cycling process were not severe on the concrete itself.

iii) Normal out-of-group strength variation of the concrete mixes seems to have its effect on the trend of the results also. Table 4.1 and Fig. 4.1 show that the four groups of beams tested after 0, 50, 100, 150 H/C cycles were made from the concrete mixes # 3, 4, 2 and 1 respectively, and show also the average compressive strength of the control cylinder for the different mixes.

Turning our attention now to the behavior of repaired beams with epoxies A, B and C as depicted in Fig. 4.9, further observations are made, among which are the following:

C) At 0 H/C cycles the repair of grooved beams with the three kinds of epoxies has brought the strength of these repaired beams (A, B and C) back to almost the strength of the solid ungrooved reference beams(S). This was manifested by a tensile failure away from the repair area (Plate 4.1) or mostly in concrete at the repaired crack as was mentioned in Section 4.3.1.

D) As the number of H/C cycles increased, a marked decrease in the flexural strength of the repaired specimens (A, B and C) was clearly obtained. This systematic decrease brought the strength of these specimens to an asymptotic behavior towards the grooved unrepaired beams (G). This means that as the number of H/C cycles increases, the

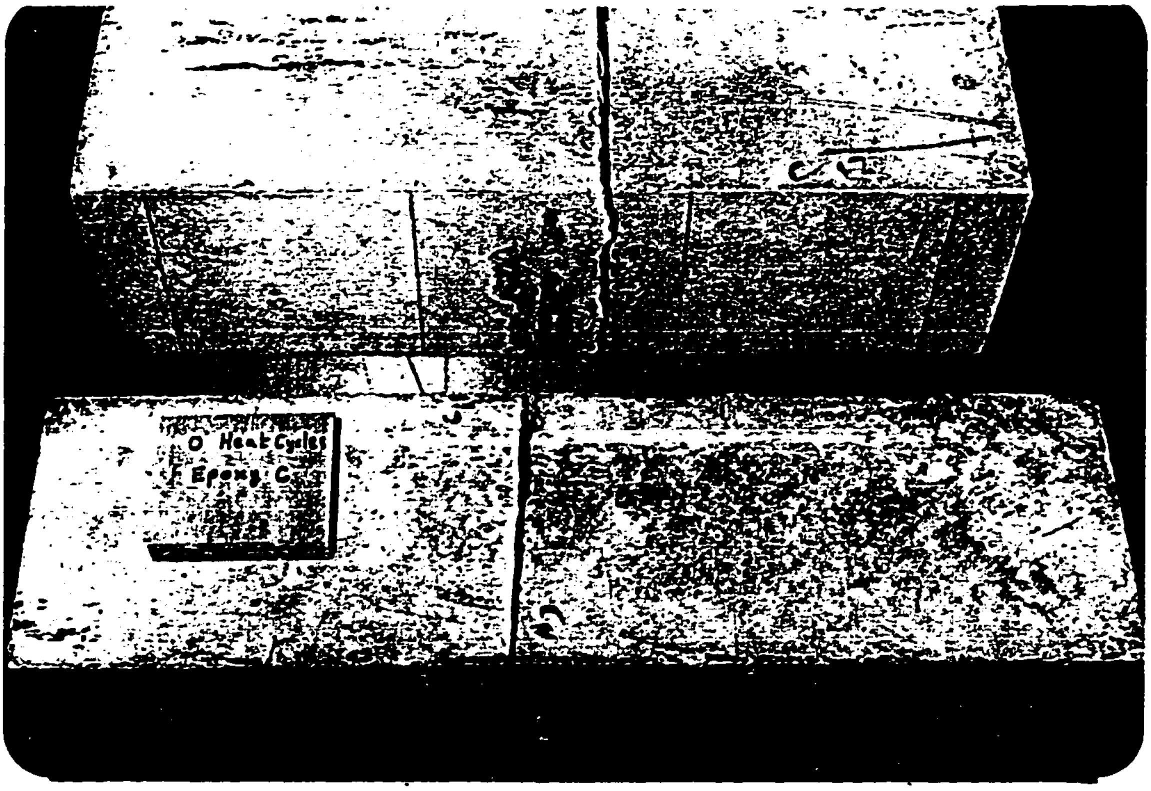


Plate 4.1: Repaired beams with epoxy C tested after 0 H/C cycles with a mode of failure in concrete away from the repair section.

Plate 4.2: Repaired beams with epoxy B tested after 100 H/C cycles with a mode of failure at the repair section.

epoxy product A, B and C tend to lose their bonding capabilities and ultimately they may become totally ineffective.

E) The slight increase in the flexural strength of beams repaired by product (A) after 150 H/C cycles can be justified as being an out-of-group variation in concrete strength, rather than an increase in the bonding strength of the product.

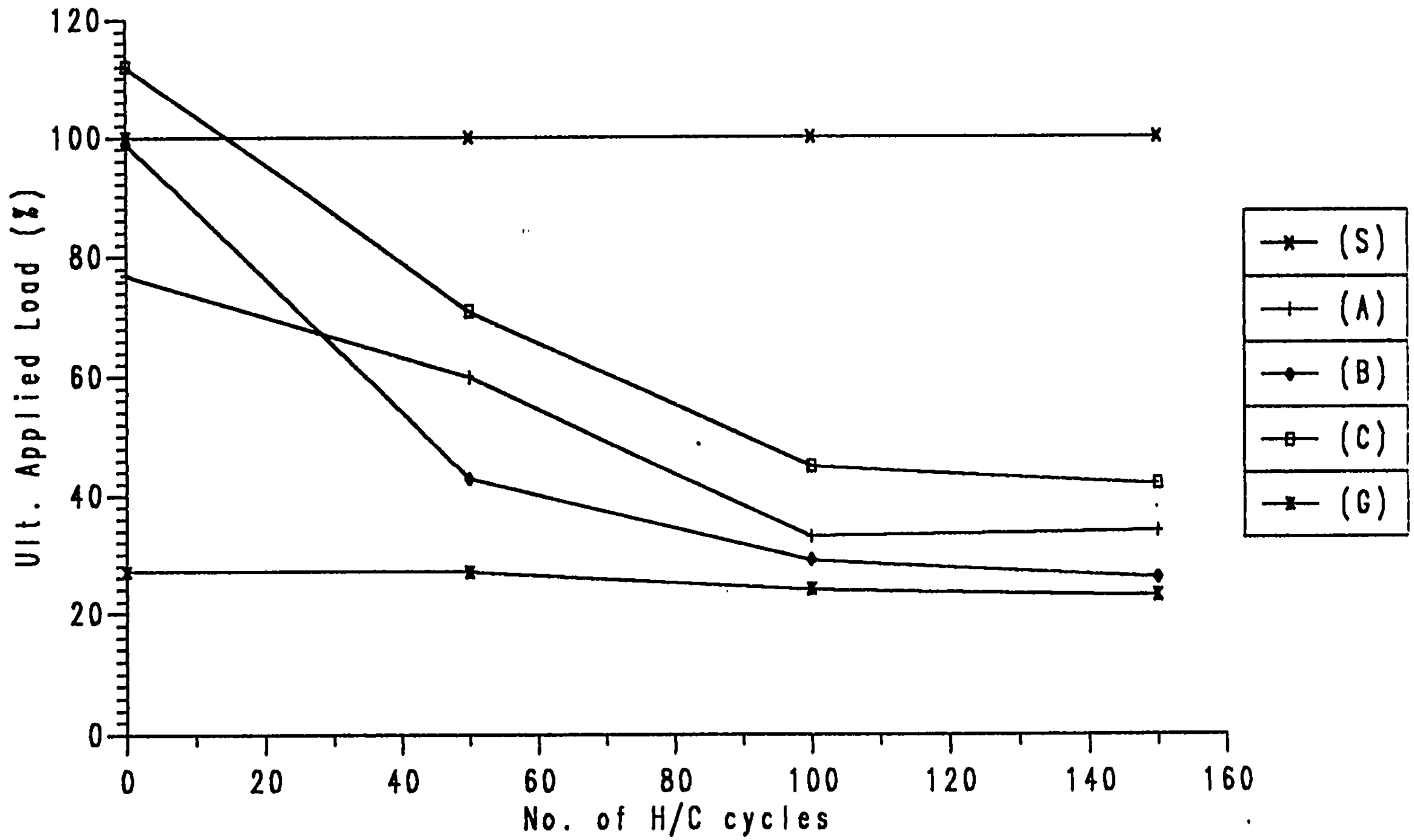
F) A common debonding failure was observed for all the repaired beam specimens with some traces of concrete attached to the epoxy layer at 50 H/C cycles (Plate 4.2) and with no traces of concrete at 100, 150 H/C cycles. This is a clear manifestation of the reduction in their bonding strengths after a limited number of H/C cycles.

To further illustrate the behavior of the epoxy repaired beams (A, B, and C) under the effect of (H/C) cycles, one can refer to Table 4.9 and Fig. 4.10, where the strength of each group of beams of a certain number of H/C cycles were calculated as percentages of the strength of the solid ungrooved beams (S) of the same number of H/C cycles. This figure shows the strengths of repaired beams (A, B, C) as bounded by an upper limit at 0 H/C cycles, where this limit is represented here by the strength of solid beams (S), and by a lower limit at 150 H/C cycles, where it is represented by the strength of grooved beams (G). To clearly illustrate this phenomena, one can combine the behavior of the three types of repaired

Table 4.9: Effect of Heat-Cool Cycling on the Flexural Strength of Epoxy-Injected Repaired Beams (as Percentage of the Strength of Solid Beams (s)

Specimen Type	Ultimate Applied Load (%)			
	0 H/C Cycles	50 H/C Cycles	100 H/C Cycles	150 H/C Cycles
Solid Ungrooved (S)	100.0	100.0	100.0	100.0
Grooved Repaired with epoxy A (A)	77.0	60.4	32.9	33.7
Grooved Repaired with epoxy B (B)	99.4	42.7	29.1	26.2
Grooved Repaired with epoxy C (C)	112.2	71.4	44.8	41.6
Grooved Unrepaired with epoxy (G)	27.4	26.9	24.5	23.4

Fig. 4.10: Effect of Heat-cool Cycling on the Flexural Strength of Epoxy-injected Repaired Beams (as Percentage of (S) Value)



beams (A, B and C) in a single average curve representing the three repair products. Fig. 4.11 shows clearly the degradation of the flexural capacity of such averaged repaired beam (R) subjected to an increasing number of H/C cycles.

In order to consider the performance of the bond between epoxy and concrete under an increasing number of H/C cycles, one can calculate the contribution of epoxy-concrete bond to the flexural capacity of repaired beams beyond the contribution of the grooved unrepaired beams (G). This is achieved by subtracting the strength of grooved beams (G) from the total strength of repaired beams of the same group (same number of H/C cycles). Results are listed in Table 4.10 and clearly shown in Fig. 4.12. This figure shows the marked degradation in the bond flexural capacity between epoxy and concrete as the number of heat-cool cycles increased. Table 4.11 and Fig. 4.13 show this degradation in terms of the percentage loss in the bond flexural capacity as calculated in the following equation:

$$\%\ \text{loss} = \frac{P_{o\ H/C} - P_{n\ H/C}}{P_{o\ H/C}} \times 100$$

where:

$P_{o\ H/C}$ = Flexural strength contribution of the bond between the epoxy product and concrete at zero heat-cool cycles.

$P_{n\ H/C}$ = Flexural strength contribution of the bond between the epoxy product and concrete after n heat-cool cycle.

Fig. 4.11: Effect of Heat-cool Cyclingon the Average Flexural Strength of Repaired Beams (as Percentage of (S) Value)

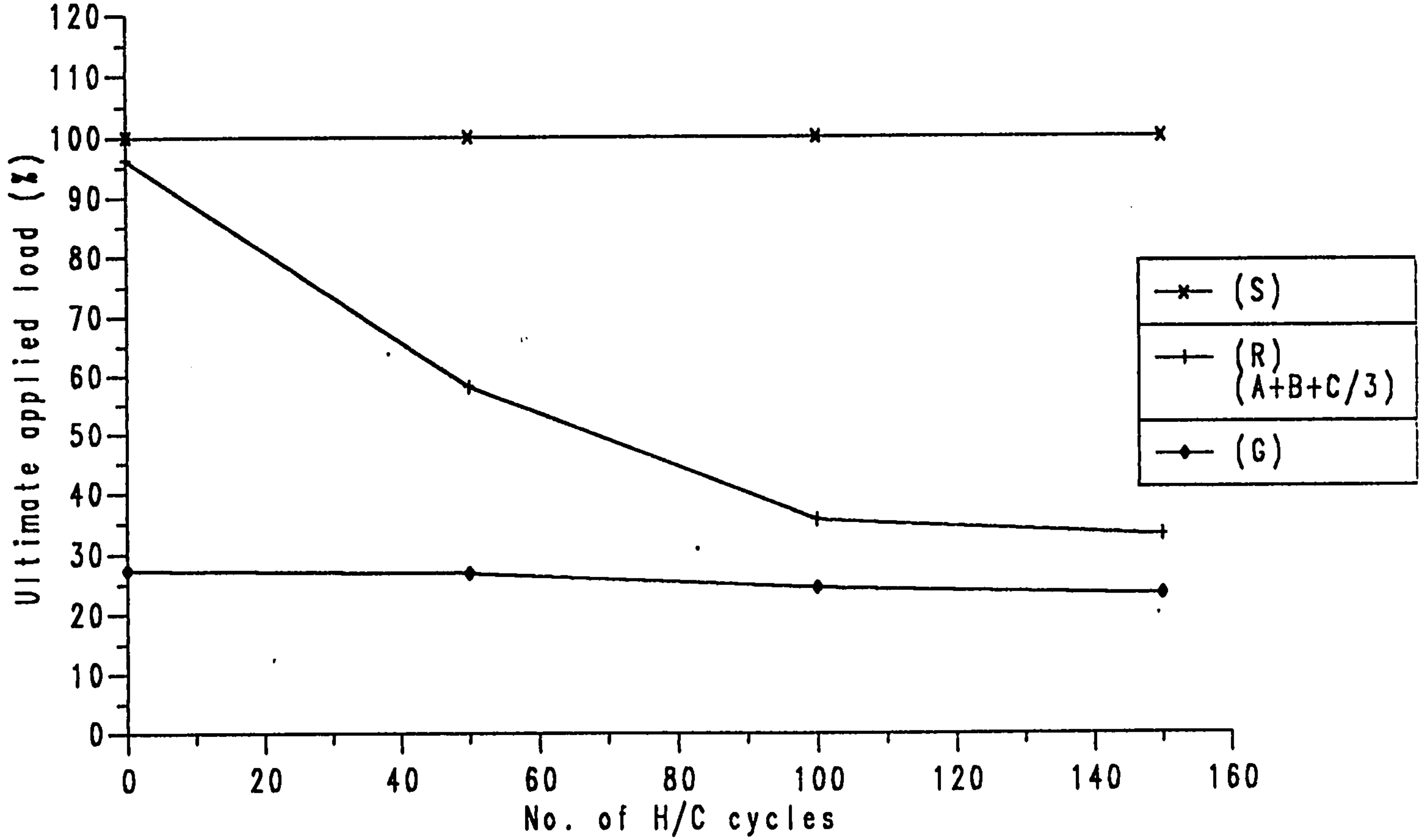


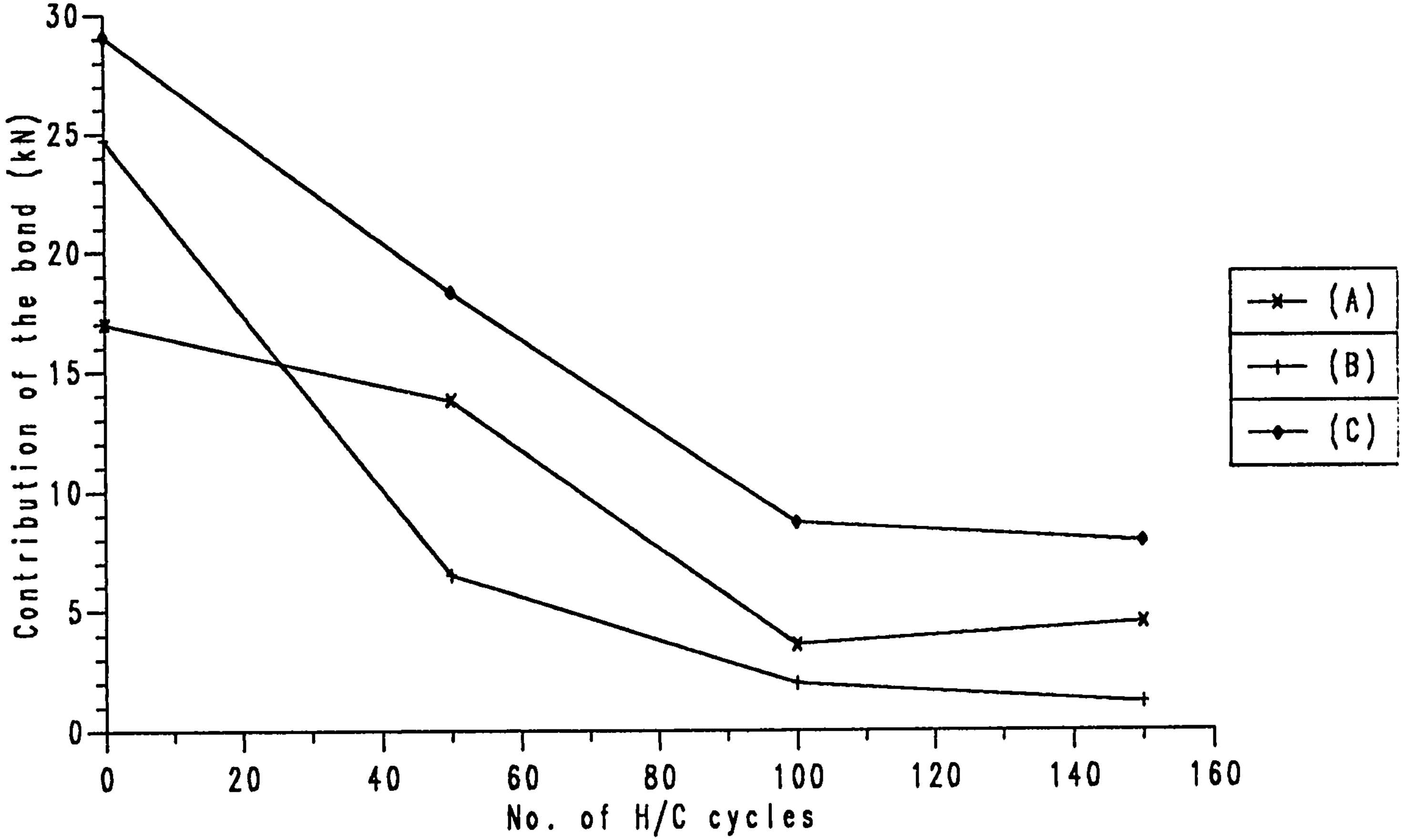
Table 4.10: Effect of Heat-Cool Cycling on the Contribution of the Epoxy-Concrete Bond to the Ultimate Strength of Flexural Beams (kN)

Specimen Type	Ultimate Applied Load (kN)			
	0 H/C Cycles	50 H/C Cycles	100 H/C Cycles	150 H/C Cycles
Grooved Repaired with epoxy A (A)	17.0	13.8	3.6	4.5
Grooved Repaired with epoxy B (B)	24.7	6.5	2.0	1.2
Grooved Repaired with epoxy C (C)	29.1	18.3	8.7	7.9

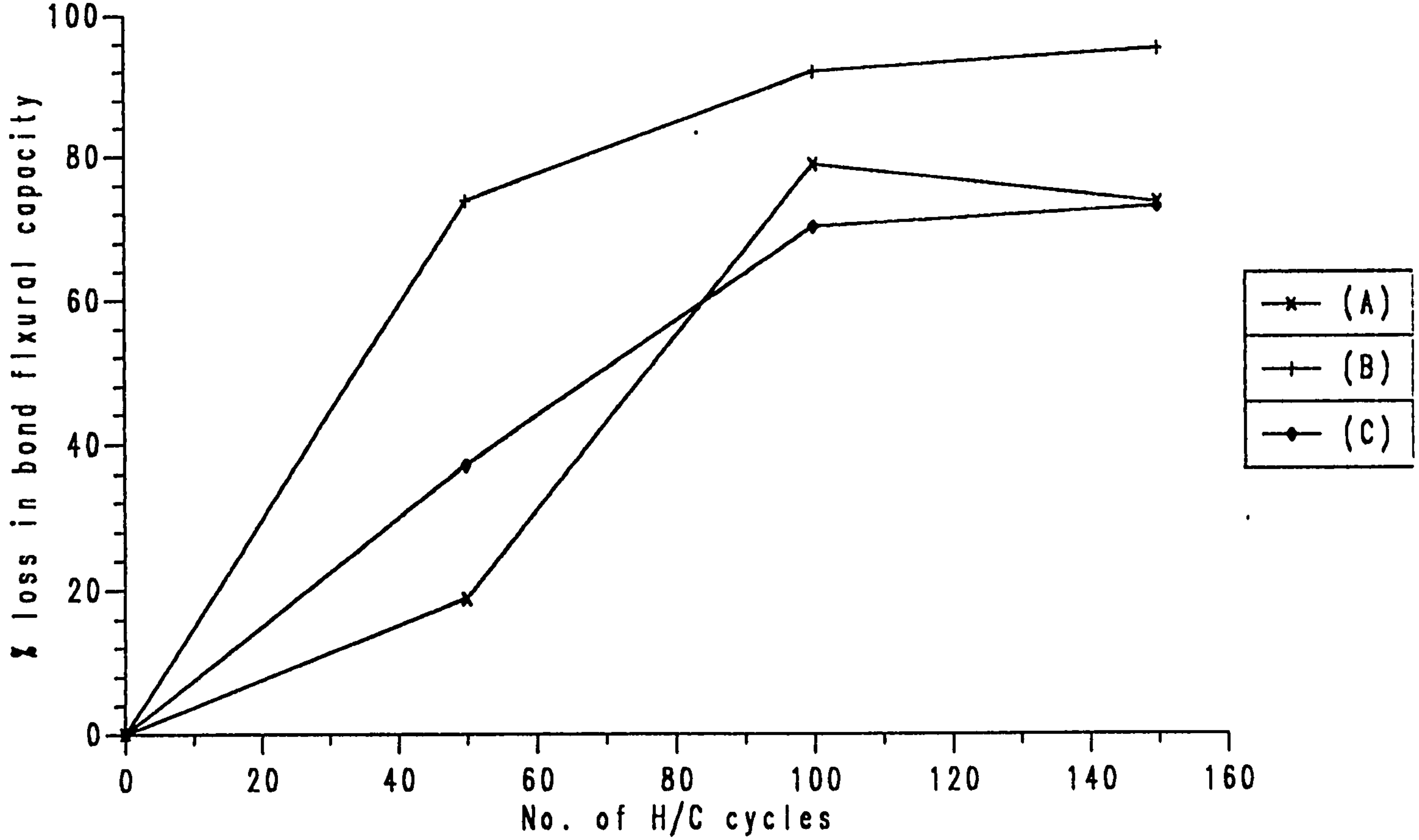
Table 4.11: Percentage Loss in Bond Flexural Capacity Between Epoxy and Concrete due to the Heat-Cool Cycling (in terms of the Bond Flexural Capacity at 0 H/C Cycles)

Specimen Type	0 H/C Cycles	50 H/C Cycles	100 H/C Cycles	150 H/C Cycles
Grooved Repaired Beams with epoxy A (A)	0	18.8	78.0	73.5
Grooved Repaired Beams with epoxy B (B)	0	73.7	91.9	95.1
Cracked Repaired Beams with epoxy C (C)	0	37.1	70.1	72.9

Fig. 4.12: Effect of Heat-cool Cycling on the Contribution of Epoxy-concrte Bond to the Ultimate Strength of Flexural Beams (kN)



Fif. 4.13: % Loss in Epoxy-concrete Flexural Bond Capacity due to Heat-cool Cycling (in terms of Bond Capacity @ 0 H/C Cycles)



Epoxy product B lost almost 95% of its flexural bond capacity after 150 heat-cool cycles while epoxies A, C lost almost 75% of their bonding capacity after the same number of cycles.

The degradation in bond between epoxy and concrete as the number of heat-cool cycles increased is believed to be due to the difference in the coefficients of thermal expansion of each type of epoxies used and that of concrete, which lead to the development of repetitive thermal stresses (thermal fatigue) with the heat-cool cycling process, which lead to the bond line failure between the epoxy layer and concrete. It is well known that there is a large difference between concrete and cured epoxies in their coefficients of thermal expansion [6]. Epoxies have coefficients of thermal expansion in the range of 1.4 to 18.7 times as high as concretes [37]. As seen in the table of properties of the three types of epoxies used (Table 3.2), the coefficients of thermal expansion of epoxies A, B and C are 60×10^{-6}, and 90×10^{-6} and 50×10^{-6} per ^{0}C (33.3×10^{-6}, and 50×10^{-6} and 27.8×10^{-6} per ^{0}F) , respectively. On the other hand, the coefficient of thermal expansion of concrete used, which is made of Abu-Hadriyah crushed aggregate, is in the vicinity of 12×10^{-6} per ^{0}C 6.7×10^{-6} per ^{0}F) [47]. We notice that as the difference in the coefficients of thermal expansion between epoxy and concrete increased, the degradation due to the heat-cool cycling also increased. This is quite shown in Figs. (4.9, 4.10).

4.4.2 *Heat-Cool Cycling of Epoxy-Injected Cylinders*

Tests conducted on cracked and epoxy-injected concrete beams showed that the tensile bond strengths across the concrete-epoxy interface tend to deteriorate rapidly when subjected to an increasing number of heat-cool cycles. It is the objective of this phase of the study to examine the effect of H/C cycles on the epoxy-concrete bond behavior under combined compressive and shear stresses. This can be achieved by subjecting the repaired cylinders to H/C cycles and testing them in axial compression (Fig. 3.3).

Four groups of cylinders were used in this study, these groups have undergone 0, 100, 200 and 316 H/C cycles (also, the group of 0 H/C cycles was actually the same group of cylinders which was tested at 20°C = 68°F and which was mentioned in Section 4.3.2). Each group consisted of two complete cylinders and two cracked and bonded cylinders for each of the repair products A, B and C. Each heat-cool cycle consisted of placing cylinders for 6 hours in the over set at 70°C (158°F), followed by 6 hours in room temperature at 20°C (68°F) and it was found that the maximum temperature gained during the cycle was 65°C ± 3°C) (149°F ± 5.4°F). After the completion of the specified number of cycles for each of the four groups, cylinders were tested in compression at room temperature, after at least seven days from the end of their cycling process. Results of these tests are presented in Table 4.12 and are plotted graphically in Fig. 4.14.

Considering Fig. 4.14, the following observations can be made:

A) The group of cylinders denoted by (S) represents the effect of H/C cycling on the compressive strength of solid uncracked concrete cylinders. It is observed that as the number of H/C cycles increases from 0 to 200, the concrete gains extra strength in the neighbourhood of 10% of its original fc'. After 316 H/C cycles the concrete loses this gain and goes back to its initial fc' approximately. The causes for the increase in fc' are probably related to age of concrete and possibility of hydration of the unhydrated cements at higher temperature. The concrete age at the start of cycling was about 70 days, so naturally the extra 100 days would have contributed to its strength. The slight decrease in concrete strength at 316 H/C cycles could be related to the presence of micro cracks due to H/C cycling and/or out-of-group strength variations.

B) Behaviour of epoxy injected cylinder groups (A) and (C) exhibited a very compatible pattern to each other and closely followed that of the uncracked cylinders (S). This pattern is characterized by an average of about 9% reduction in strength below that of the (S) cylinders of the H/C cycling program. The pattern of failure for these cylinders (A and C) was also compatible to that of the (S) cylinders, i.e. was characterized by the cracking and crushing of the

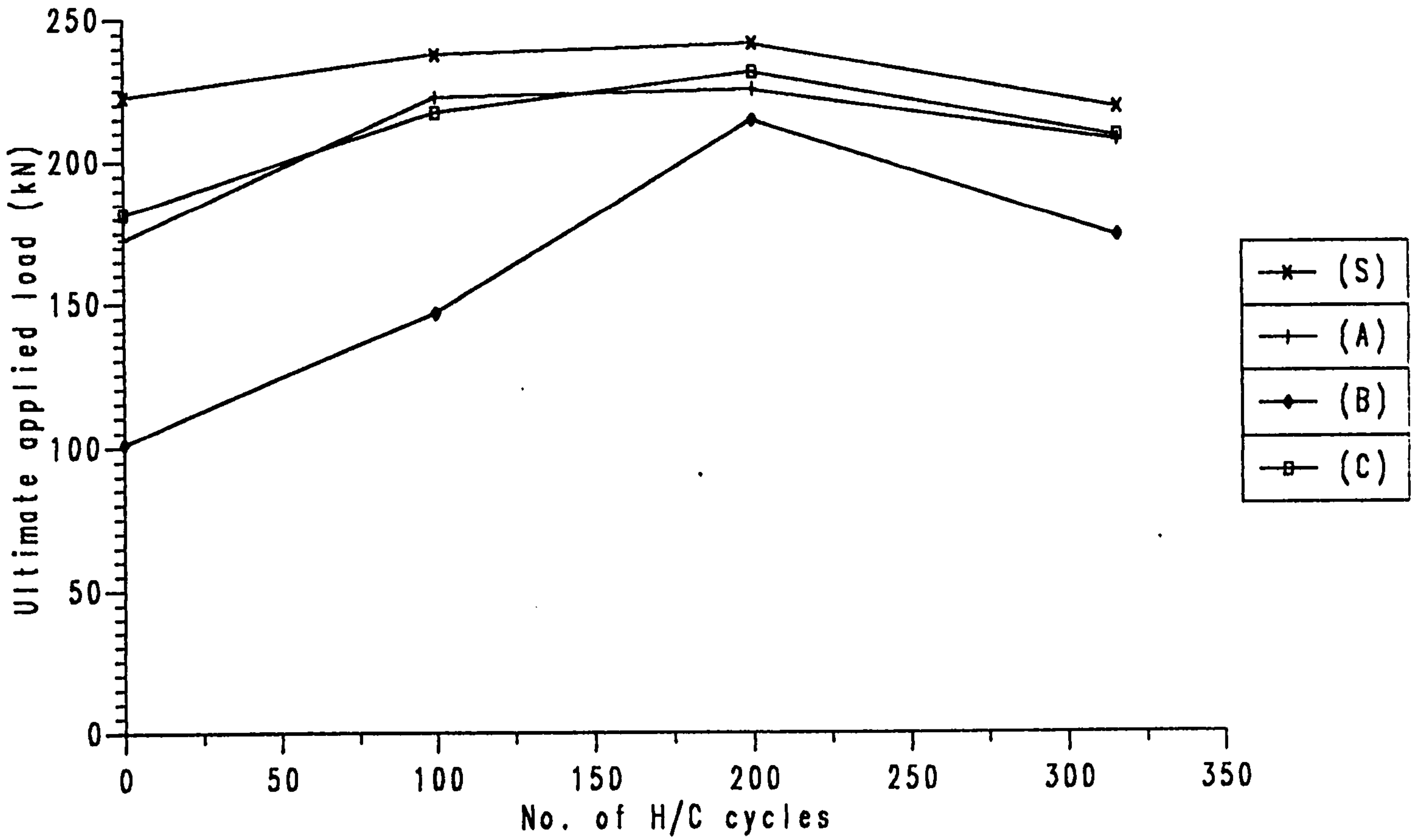
Table 4.12: Average Ultimate Applied Load of Cylindrical Specimens Tested in Compression After H/C Cycling Program (kN)

Specimen Type	0 H/C Cycles	100 H/C Cycles	200 H/C Cycles	316 H/C Cycles
Solid Uncracked (S)	222.6	227.5	241.0	218.3
Cracked Repaired with epoxy A (A)	172.7	222.3	224.8	207.0
Cracked Repaired with epoxy B (B)	101.0	146.5	214.0	173.5
Cracked Repaired with epoxy C (C)	181.5	217.0	230.8	208.3

Table 4.13: Average Ultimate Applied Load of Cylindrical Specimens Tested in Compression After H/C Cycling Program (as Percentage of Solid Cylinder Values)

Specimen Type	0 H/C Cycles	100 H/C Cycles	200 H/C Cycles	316 H/C Cycles
Solid Uncracked (S)	100.0	100.0	100.0	100.0
Cracked Repaired with epoxy A (A)	77.6	97.7	93.3	94.8
Cracked Repaired with epoxy B (B)	45.4	64.4	88.8	79.5
Cracked Repaired with epoxy C (C)	81.5	95.4	95.8	95.4

Fig. 4.14: Effect of Heat-cool Cycling on the Compressive Strength of Epoxy-injected Repaired Cylinders



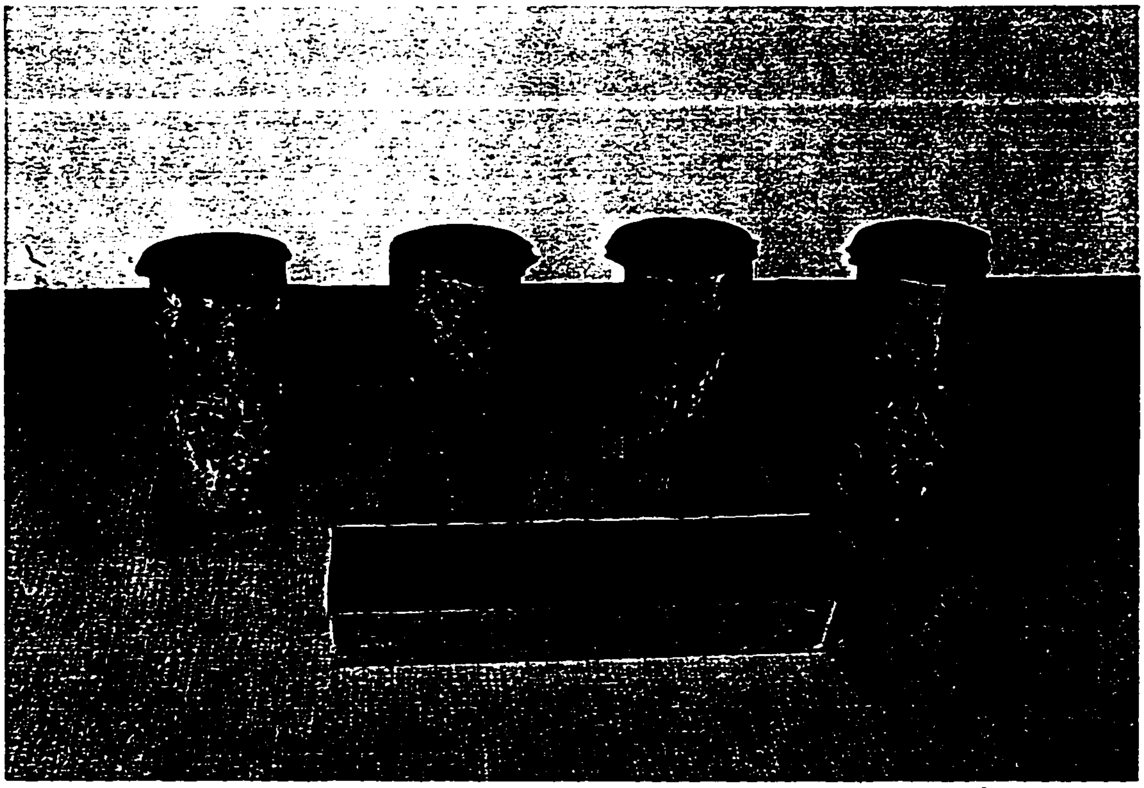


Plate 4.3: Cylinders tested after 0 cycles: (S), (A), (B) and (C), from left to right respectively.

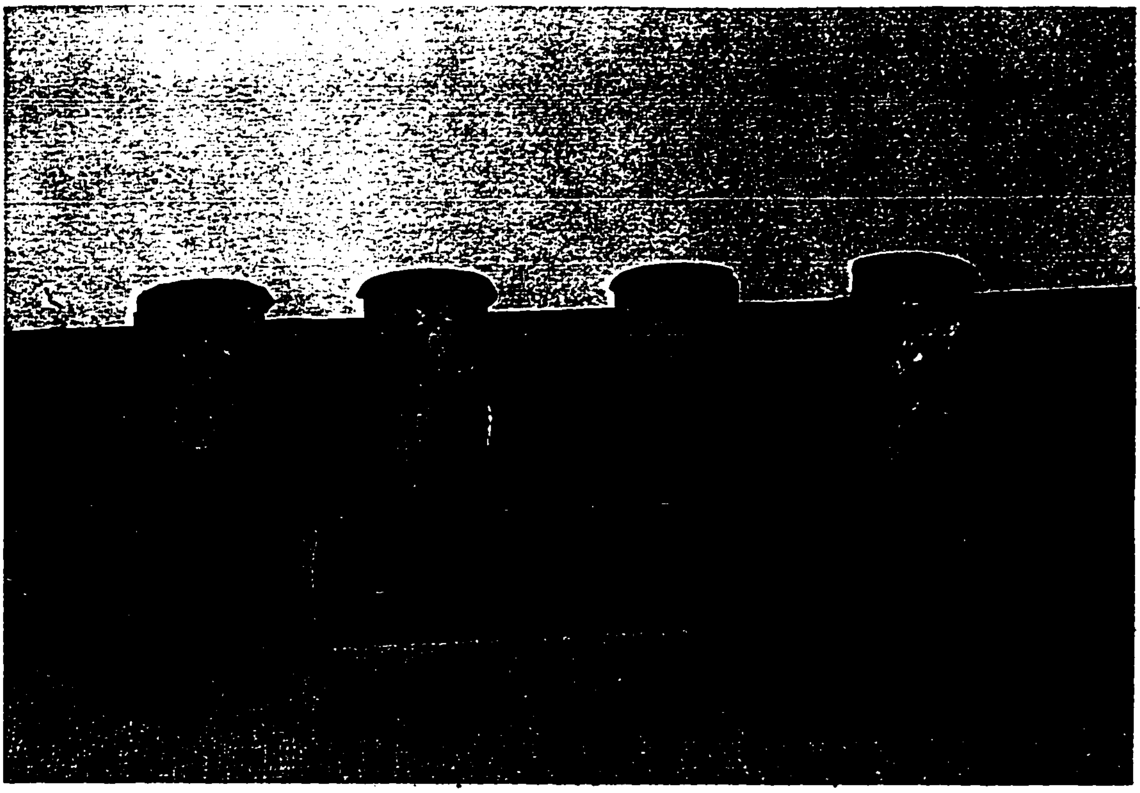


Plate 4.4: Cylinders tested after 316 H/C cycles: (S), (A), (B) and (C), from left to right respectively.

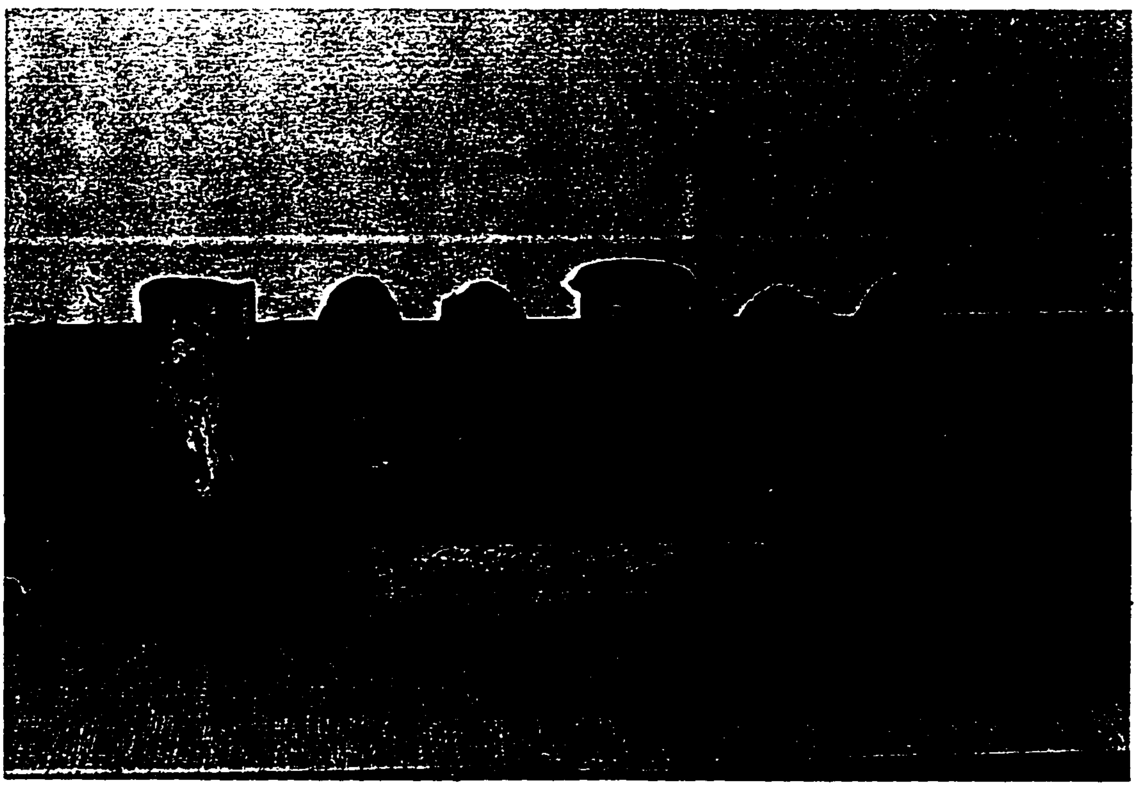


Plate 4.5: Cylinders tested after 120 W/D cycles: (S), (A), (B) and (C), from left to right respectively.

concrete middle part, leaving the well formed end cones (Plates 4.3, 4.4).

If conclusions are to be made on the basis of the behavior of the A and C repaired cylinders, it would be fair to say that epoxy repaired cylinders did not show any signs of strength degradation when subjected to an increasing number of H/C cycles and tested under compression, where the epoxy-concrete was subjected to combined compressive and shear stresses.

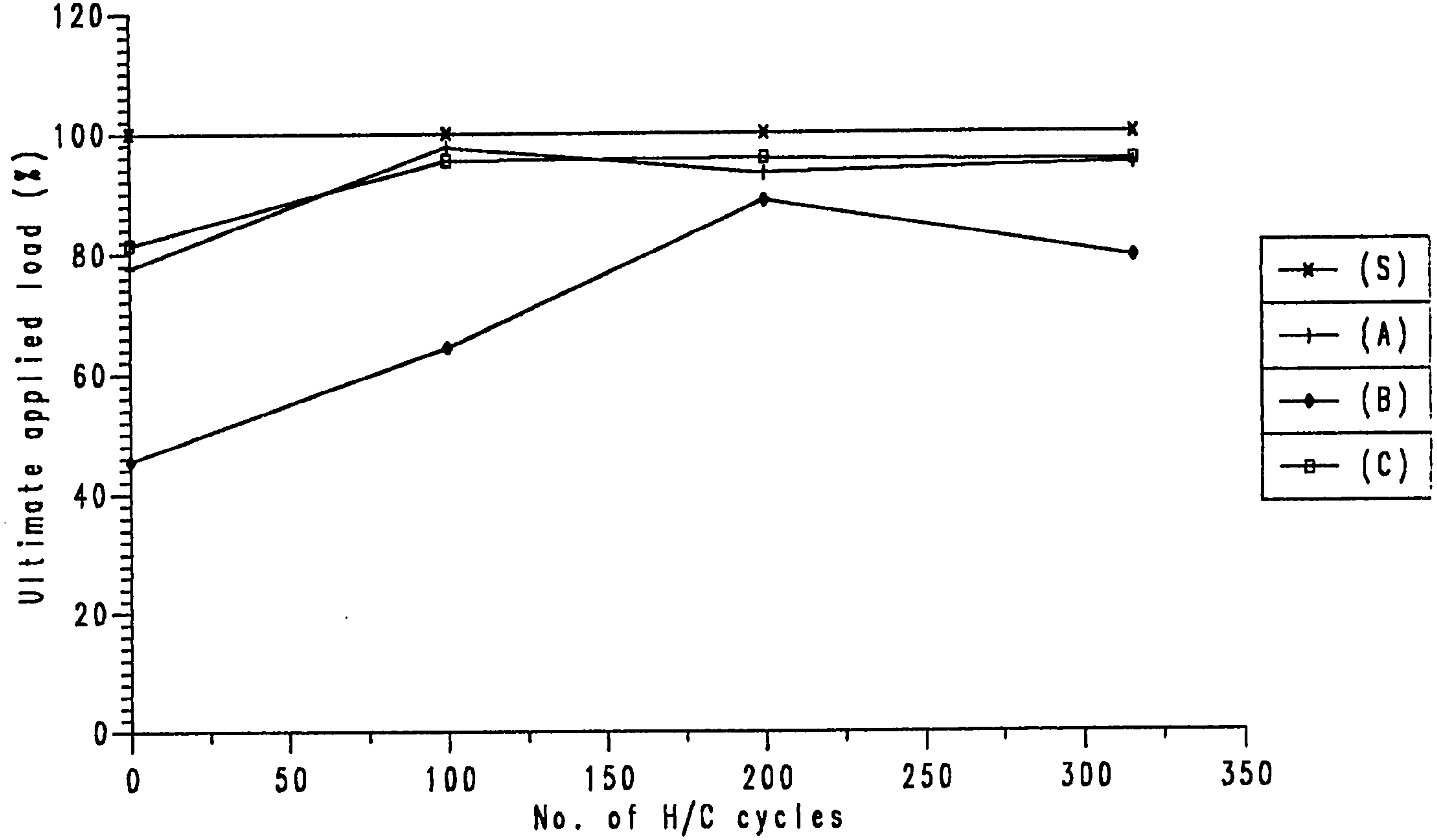
C) Cylinders repaired with epoxy B showed lower values of strength at 0 and 100 H/C cycles (45% of the strength of solid cylinders at 0 H/C cycles), while they produced comparable strengths at higher number of H/C cycles. They failed in shear through the slant bond line between epoxy and concrete except at 200 H/C cycles, where the crushing of concrete resulted in the conic pattern of failure. This behaviour can be justified as being due to an experimental error or due to the late use of epoxy B near from the end of its shelf life.

Epoxy product B was supplied in packages, each of which contained premeasured can of epoxy resin and a can of hardener weighing together 2 kgs. The amount of epoxy needed for each injection process was collected from the two cans and mixed together according to the mixing ratio and then injected into the cracked cylinders. The repair of cylinders used in this study by epoxy injection using the three kinds of epoxy was made on different intervals ranging from zero to nine months from the first time they were used. Specimens of large number of cycles were epoxy injected at earlier times. A group or more of specimens, each of which have similar conditions, were epoxy injected together with the three kinds of epoxy products used in this study. The experimental error could be in the preparation of cracked cylinders, which might lead to the misalignment of the two halves on top of each other, in the mixing of the two components of epoxy B together before application, or in the injection process of this epoxy into the cracked cylinders. In view of the considerable care taken in the experimental work in order to have consistency and accuracy of the test results the second reason of the late use of epoxy B near from the end of its shelf life seems to be more plausible: it is given in the technical data sheet of epoxy B that the shelf life of it is 12 months when unopened and stored correctly. Our records showed that about nine months have elapsed between our first opening of the sealed cans and the date of injecting cylinders of the H/C cycling program. Epoxy C was used in the same way as epoxy B was used, while epoxy A was used by using a new prepacked cartridge of resin with a new tube of hardener to produce a suitable quantity of the epoxy compound as needed. Cylinders repaired with the two other epoxy products A and C were injected at the same time of injecting epoxy B into its cylinders, but they did not show a degradation due to this factor. However, it can be concluded from the strength results of repaired cylinders with epoxy B that no signs of degradation due to the H/C cycling process were obtained, which consists with the results of cylinders repaired with epoxies A and C.

A better method of assessing the response of epoxy-injected cylinders under the H/C cycling is to evaluate their compressive strength values as percentages of the solid uncracked cylinders (S) of the same number of H/C cycles. Table 4.13 and Fig. 4.15 show such data. By doing that, the out-of-group strength variation is excluded from the results since the cylinder strengths were expressed in terms of the solid strengths of the same concrete mix. We can notice the similarity in the trend of results in the two figures (Figs. 4.14 and 4.15).

We can conclude from the trend of the results, particularly those of cylinders repaired with epoxy A and C, that no adverse effect due to the H/C cycling was noticed on the repaired cylinders when tested in compression while cool after the specified number of cycles. In fact, we believe that the slight reduction in the crushing strength of the repaired cylinders, and in particular at 0 H/C cycles, is mostly due to the method used in the preparation of

Fig. 4.15: Effect Oo Heat-cool Cycling on the Compressive Strength of Epoxy-injected Repaired Cylinders (as Percentage of (S) Value)

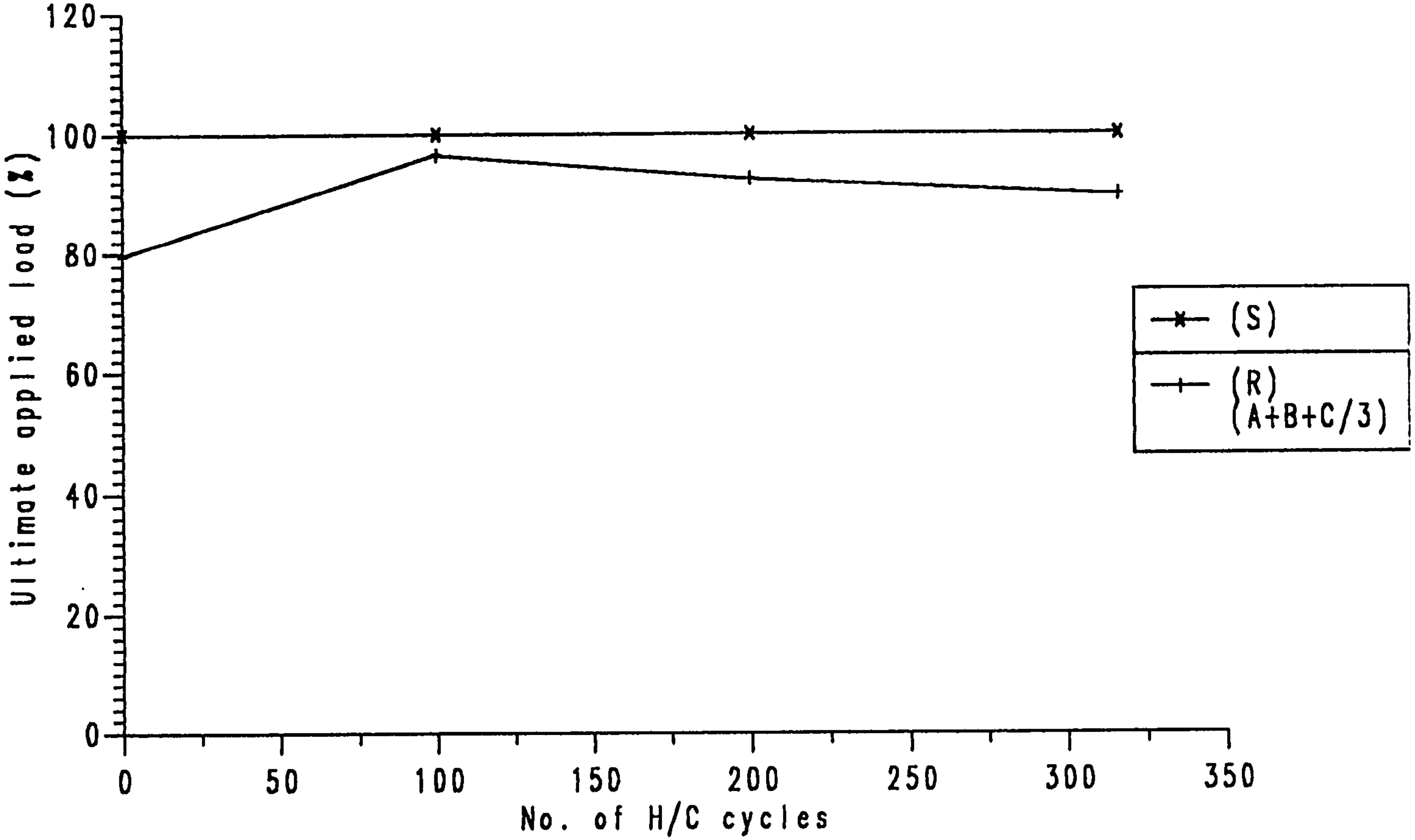


cracked cylinders. This method consisted of fixing one half cylinder on top of the other by tightening a steel ring of ½ inch (12 mm) width around the two halves, and keeping a slant gap (crack) 1.6 mm (1/16 in) between them using metal strips as separators, which were removed later at the time of injection (see Section 3.4.2, Plate 3.10). This procedure which included hand adjustments seemed to be not accurate enough to produce perfect right angle repaired cylinders, and thus resulted in the lower values obtained for the repaired cylinders.

As a final representation of the test results, Fig. 4.16 shows the average values of the compressive strength of repaired cylinders with epoxy products A, B, C as percentages of solid cylinder strength values (excluding results of epoxy B at 0, 100 H/C cycles for the above mentioned points).

Although results of beam specimens revealed the negative effect of repetitive changes in temperature on the bond between epoxy and concrete, where it was subjected to linear tensile stresses, results of cylindrical specimens did not show up that effect, when the epoxy-concrete bond was subjected to combined compressive and shear stresses. It is believed that heat-cool cycling regime applied on the cylinders could not degrade the bond between epoxy and concrete, where the strong shear resistance of the bond itself enhanced by the frictional force resulting from the compression component of the applied load and also enhanced by having the crack surface rough-

Fig. 4.16: Effect of H/C Cycling on the Average Compressive Strength of Repaired Cylinders (as Percentage of (S) Value)



ened by sand blasting before injection, could withstand the shear force component of the applied load, and thus no shear failure through the bond line occurred before the crushing strength of concrete cylinders. Therefore, a more severe H/C cycling program or a larger number of H/C cycles of the used program is expected to have a negative effect on the epoxy-concrete bond strength in repaired cylinders.

Also it is preferred to use another method for the preparation of cracked specimens, which would be a more accurate and easier one, possibly the method mentioned in BS6319:Part 4:1984 for the measurement of bond strength by the slant shear method [21].

4.5 Results of Wet-Dry Cycling Program of Repaired Cylinders

The coastal regions of the Red Sea and the Arabian Gulf are characterized by high humidity levels coupled with high temperatures. humidity levels reaching around 95-100% are not uncommon in these regions. A wet/dry (W/D) cycling program was established to simulate these extreme conditions. Each cycle would consist of immersion of the samples in water (at room temperature) for 12 hours, followed by placing these samples in an oven for 6 hours, the oven is set at 70°C (158°F) temperature. This is followed by a cool down period of 6 hours to bring them back to the room temperature at 20°C (68°F). So, each W/D cycle would consume 24 hours.

Due to the laborious efforts involved in this W/D cycling regime, only samples of moderate size could be involved in this experiment, so a decision was made to restrict this test to repaired cylinders, as it was not quite feasible to handle the large beams in this program. Three groups of cylinders were subjected to 0, 80 and 120 W/D cycles, with the first group of 0 W/D cycles being actually the same group of cylinders of 0 H/C cycles and 20°C = 68°F test temperature which was mentioned in previous sections. The original design of this experiment was to include larger number of W/D cycles, but time restrictions have enabled us to gather data at 80 and 120 W/D cycle levels only. Each of the three cylinder groups consisted of two solid uncracked (S) reference cylinders, and two repaired cylinders with each of the epoxy products A, B and C.

The cylinders would be tested in compression (Fig. 3.3) after at least 7 days from the completion of the specified number of cycles and the test is conducted at room temperature. Results of these tests are given in Table 4.14 and are illustrated graphically in Fig. 4.17. The following observations are noted from this set of data:

A) The data provided by cylinder groups (S) indicates the concrete compressive strength behaviour with the increasing number of W/D cycles. This behaviour is manifested by about 20% increase in fc' values after the first 80 W/D cycles, followed by a slight decrease in the fc' values as the W/D cycles increased to 120 cycles. It is understanda-

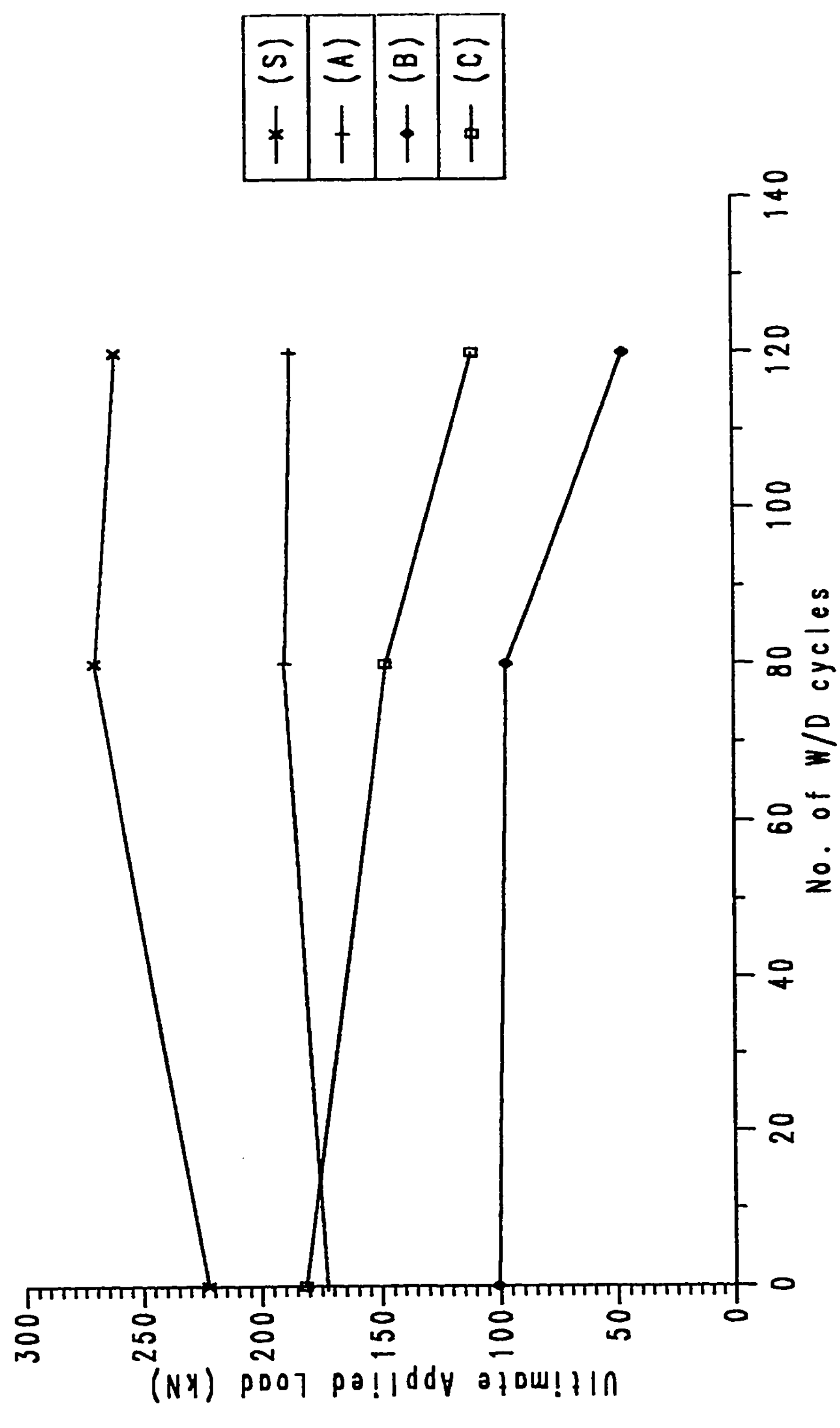
Table 4.14: Average Ultimate Applied Load of Cylindrical Specimens Tested in Compression After W/D Cycling Program (kN)

Specimen Type	0 W/D Cycles	80 W/D Cycles	120 W/D Cycles
Solid Uncracked (S)	222.6	270.1	260.8
Cracked Repaired with epoxy A (A)	172.7	189.2	186.5
Cracked Repaired with epoxy B (B)	101.0	96.6	46.8
Cracked Repaired with epoxy C (C)	181.5	147.5	110.3

Table 4.15: Average Ultimate Applied Load of Cylindrical Specimens Tested in Compression After W/D Cycling Program (as Percentage of the Solid Cylinder Values)

Specimen Type	0 W/D Cycles	80 W/D Cycles	120 W/D Cycles
Solid Uncracked (S)	100.0	100.0	100.0
Cracked Repaired with epoxy A (A)	77.6	70.0	71.5
Cracked Repaired with epoxy B (B)	45.4	35.8	17.9
Cracked Repaired with epoxy C (C)	81.5	54.6	42.3

Fig. 4.17: Effect Of Wet-dry Cycling On
The Compressive Strength Of Epoxy-injected Repaired Cylinders



ble that the early part of W/D cycling increases fc' for the following reasons:

a) <u>Effect of Aging</u>: As the concrete gets older, it is natural that it gathers some gains in strength during its early life. The concrete age at the start of the cycling process was bout 70 days, so naturally, the extra 80 days would have contributed to its strength.

b) <u>Effect of Hydration</u>: The W/D cycling regime would certainly be an ideal course for the completion of hydration process for any amount of unhydrated cement left in the mix.

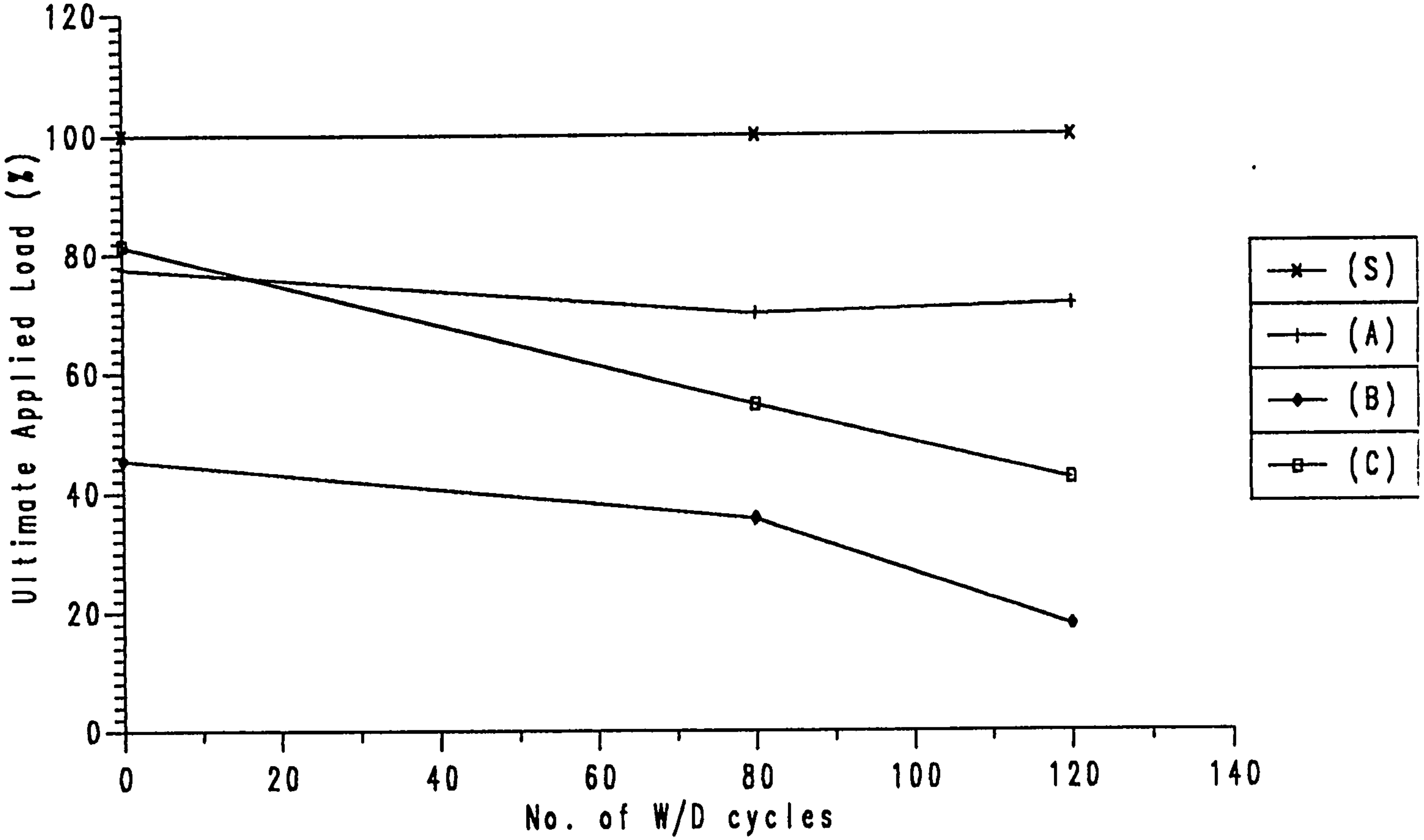
It is not clear as to what would be the real cause of the slight decrease in fc' between the 80 and 120 W/D cycles, one plausible reason would be the further development and expansion of some microcracks caused by the heat and cool cycles. Although, our cycling regime eliminated any possibility of a thermal shock (sudden change in temperature), the presence of these microcracks could not be eliminated.

To properly illustrate the effect of W/D cycling on the performance of repaired cylinders, their strength as a percentage of the (S) cylinder values is given in Table 4.15 and in Fig. 4.18. The following extra observations can be made:

B) Epoxy product A showed the most uniform behavior when subjected to an increasing number of W/D cycles. Its cylinder compressive strengths of about 77% of that for the solid cylinders (S) at 0 W/D cycles have hardly deviated from that level after 120 W/D cycles. However, the pattern of failure of its cylinders has changed from the normal conic failure of concrete cylinders at 0 W/D cycles to the shear pattern of failure through the slant bonding plane between epoxy and concrete after 80 and 120 W/D cycles (Plate 4.5). It is worth recalling here that epoxy A has good adhesion to damp concrete as was mentioned in the introduction sheet provided with it. (Table 3.2)

C) Epoxy product B showed a considerable reduction in its cylinder compressive strengths as the number of W/D cycles increased. Before cycling cylinders repaired with epoxy B attained 45% of the solid cylinder strengths with a shear mode of failure through the bond epoxy layer and concrete. That was discussed in Section 4.4.2. At 80 and 120 W/D cycles its cylinders could produce only 36, 18% of the solid cylinder strengths tested after the same number of cycles. The pattern of failure was also in shear through the bonding plane between epoxy and concrete. It is worth mentioning here also that epoxy B can be applied to damp concrete as given in the instruction sheet of this product (Table 3.2).

Fig. 4.18: Effect of Wet-dry Cycling on the Compressive Strength of Epoxy-injected Repaired Cylinders (as Percentage of (S) Value)



D) Cylinders repaired with epoxy product C showed also some serious reduction in strength at the 80 and 120 W/D cycle levels although they produced almost 82% of the solid cylinder strengths at 0 W/D cycles. At 80 and 120 W/D cycles their strength values dropped to 55, 42% respectively. The pattern of failure of these cylinders has also changed from the normal type of concrete conic failure before cycling to the shear type of failure along the bond line after 80, 120 W/D cycles.

From Table 4.15 and Fig. 4.18 a percentage loss due to W/D cycling of the bonding capacity of each of three epoxy products to concrete under combined shear and compressive stresses can be evaluated in terms of the loss in the ultimate applied load to repaired cylinders as follows:

$$\text{\% loss in bond} = \frac{P_{o\ W/D} - P_{n\ W/D}}{P_{o\ W/D}} \times 100$$

where:

$P_{o\ W/D}$ = Ultimate applied load of repaired cylinders at 0 W/D cycles as a percentage of the solid cylinder values at 0 W/D cycles.

$P_{n\ W/D}$ = Ultimate applied load of repaired cylinders at n W/D cycles as a percentage of the solid cylinder values at n W/D cycles.

This is shown in Table 4.16 and Fig. 4.19. We notice that epoxy product B lost 60% of its bonding capacity after 120 W/D cycles, and epoxy product C lost 50% of its bonding capacity while epoxy A lost only 10% of its bonding capacity after the same number of cycles.

Therefore, we can conclude that the exposure to cyclic changes similar to the W/D cyclic process described results in the degradation of the bond between epoxy and concrete. This can be thought of to be due to the following factors:

i) Repetitive stresses resulting from the frequent changes in temperature during the W/D cycling program as a result of the difference in the coefficients of thermal expansion of each type of epoxy and concrete (see sec.tion 4.4.1).

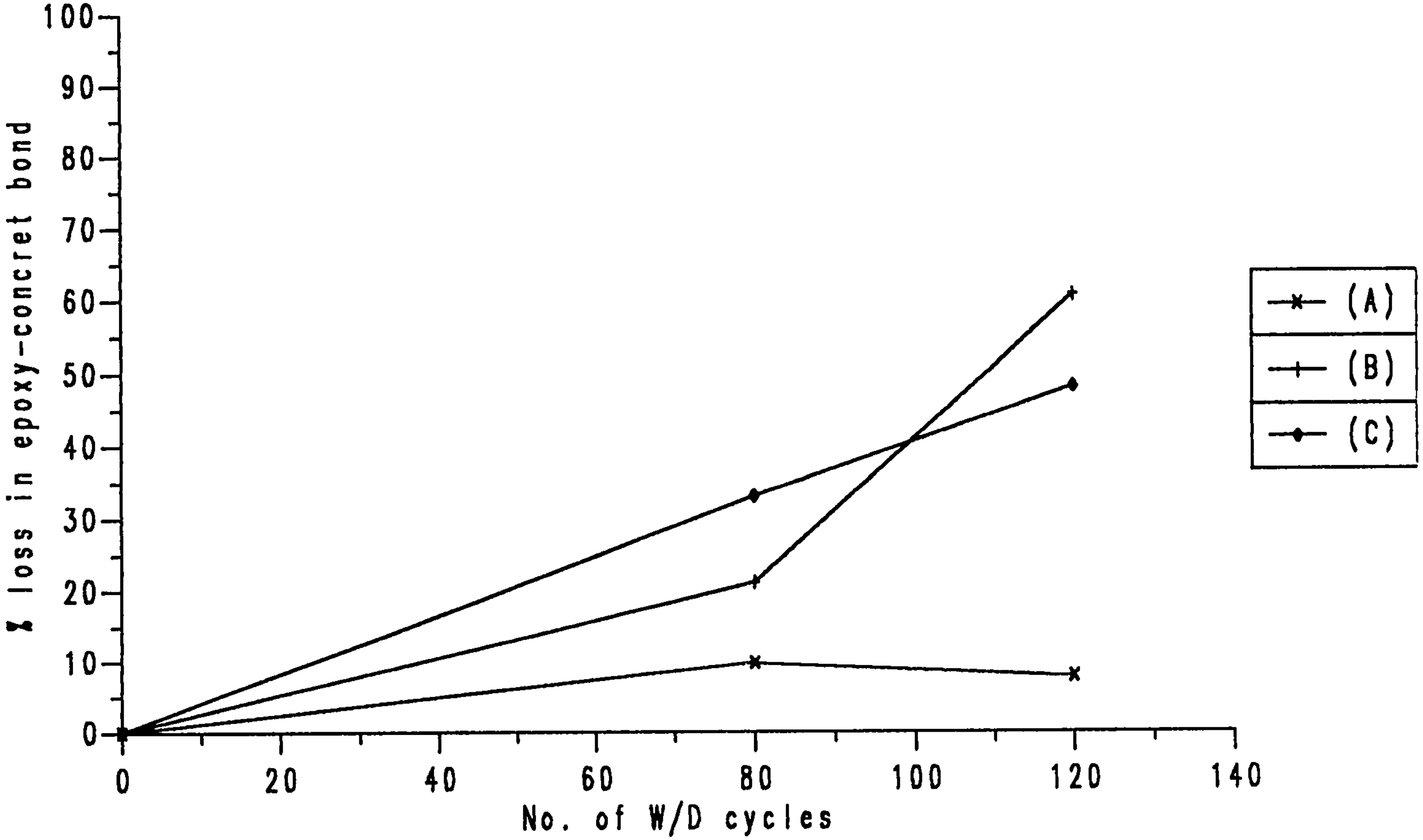
ii) Repetitive stresses resulting from the differences in volume changes between concrete and epoxy during the frequent moisture movement into and from the cylinder specimens during the W/D cycling process.

These stresses resulted in fatiguing the epoxy-concrete bond and lead to the shear failure at lower loads as shown in the results. Also, different epoxies were susceptible to different levels of degradation in their performance after exposure to a number of these cyclic changes. Finally, we would imagine that this reduction in strength would have been more pronounced, have the epoxy bonding planes been subjected to tensile strength tests instead of the combined shear and compressive stresses in these cylinders.

Table 4.16: Percentage Loss in Epoxy-Concrete Bond under Combined and Compressive Stresses in Cylinders due to W/D Cycles (in terms of the Bond Capacity at 0 W/D Cycles)

Specimen Type	0 W/D Cycles	80 W/D Cycles	120 W/D Cycles
Cracked Repaired with epoxy A (A)	0	9.8	7.9
Cracked Repaired with epoxy B (B)	0	21.1	60.6
Cracked Repaired with epoxy C (C)	0	33.0	48.1

Fig. 4.19: % Loss in Bond under Combined Compressive & Shear Stresses due to W/D Cycling (in terms of Bond Capacity @ 0 W/D Cycles)



These conclusions agree with Schupack's conclusions [37] mentioned in the literature review [see Section 2.1.4 (3)], which were based on three case studies of epoxy-concrete composites in which distress occurred after several years at the interface of epoxy and concrete. He mentioned that severe environments causing repetitive cycles such as heat-cool cycling, wet-dry cycling, and freeze-thaw cycling were mainly responsible for these distresses.

4.6 Comparison of Results

A comparison of the extent of degradation in strength of repaired concrete specimens due to the various environmental factors is made in this section as a final step in the analyses of test results. Data analyzed in details in previous sections are summarized and presented here in a manner to provide such a comparison.

4.6.1 Results of Repaired Beams

Table 4.17 and Fig. 4.20 presents the ultimate applied load (kN) at normal conditions (20°C = 68°F and 0 H/C cycles), at 62°C (143.6°F), and after 150 H/C cycles, respectively, for each type of beams (S), (A), (B) (C) and (G). The percentage losses of flexural bond capacity between epoxy and concrete at 62°C (143.6°F), and after 150 H/D cycles in comparison to flexural bond capacity at normal conditions (20°C = 68°F and 0 H/C cycles) are shown in Table 4.18 and Fig. 4.21.

Table 4.17: Comparison of the Effects of Temperature and H/C Cycling on the Flexural Strength of Epoxy-Injected Repaired Beams

Specimen Type	Ultimate Applied Load (kN)		
	Normal Conditions	@ 62°C (143.6°F)	@ 150 H/C Cycles
Solid Uncracked (S)	34.3	26.0	43.5
Cracked Repaired with epoxy A (A)	26.4	17.8	14.7
Cracked Repaired with epoxy B (B)	34.1	9.5	11.4
Cracked Repaired with epoxy C (C)	38.5	9.6	18.1
Cracked Unrepaired (G)	9.4	7.8	10.2

Fig. 4.20: Comparison of the Effects of Temperature • H/C Cycling on the Flexural Strength of Epoxy-injected Repaired Beams

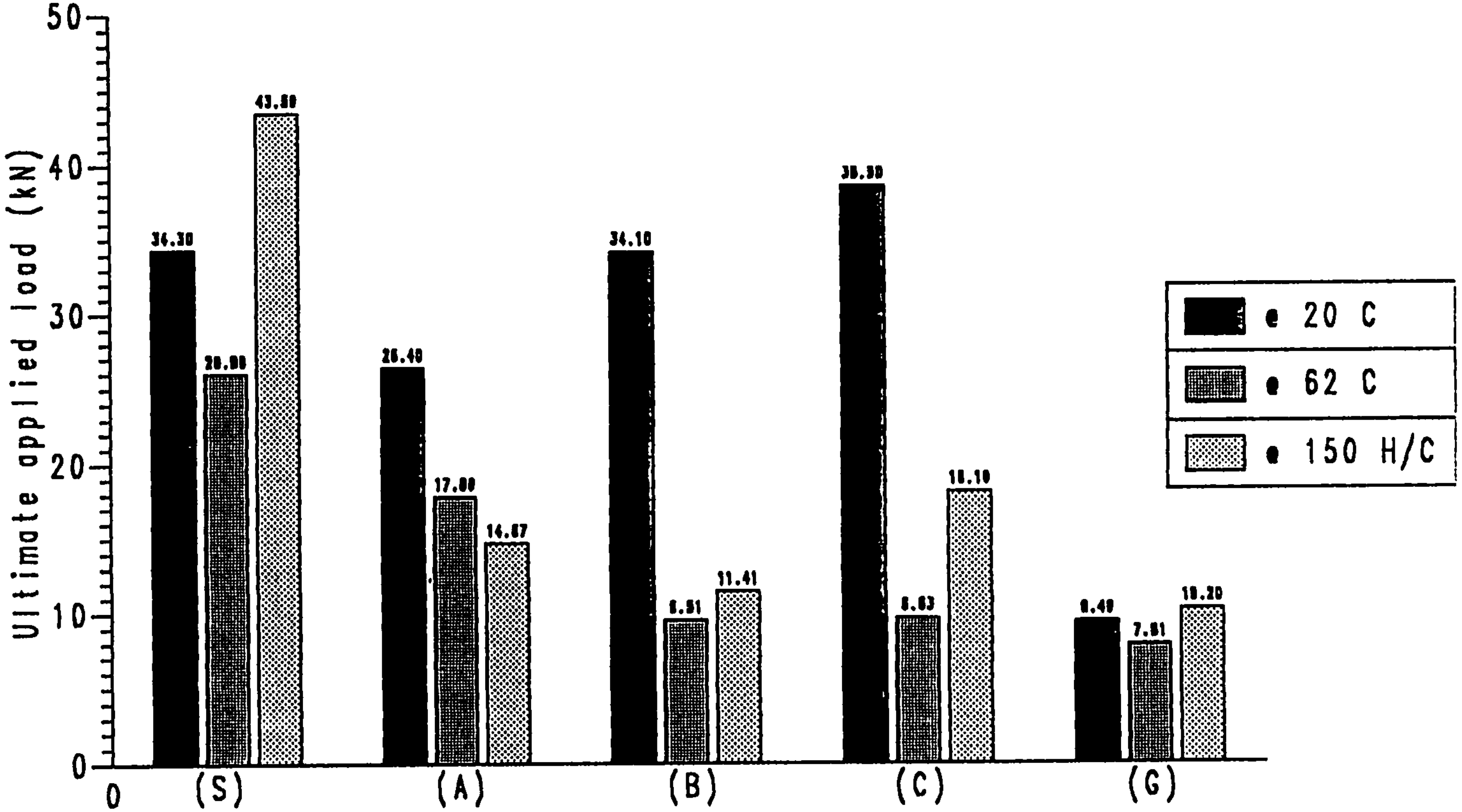
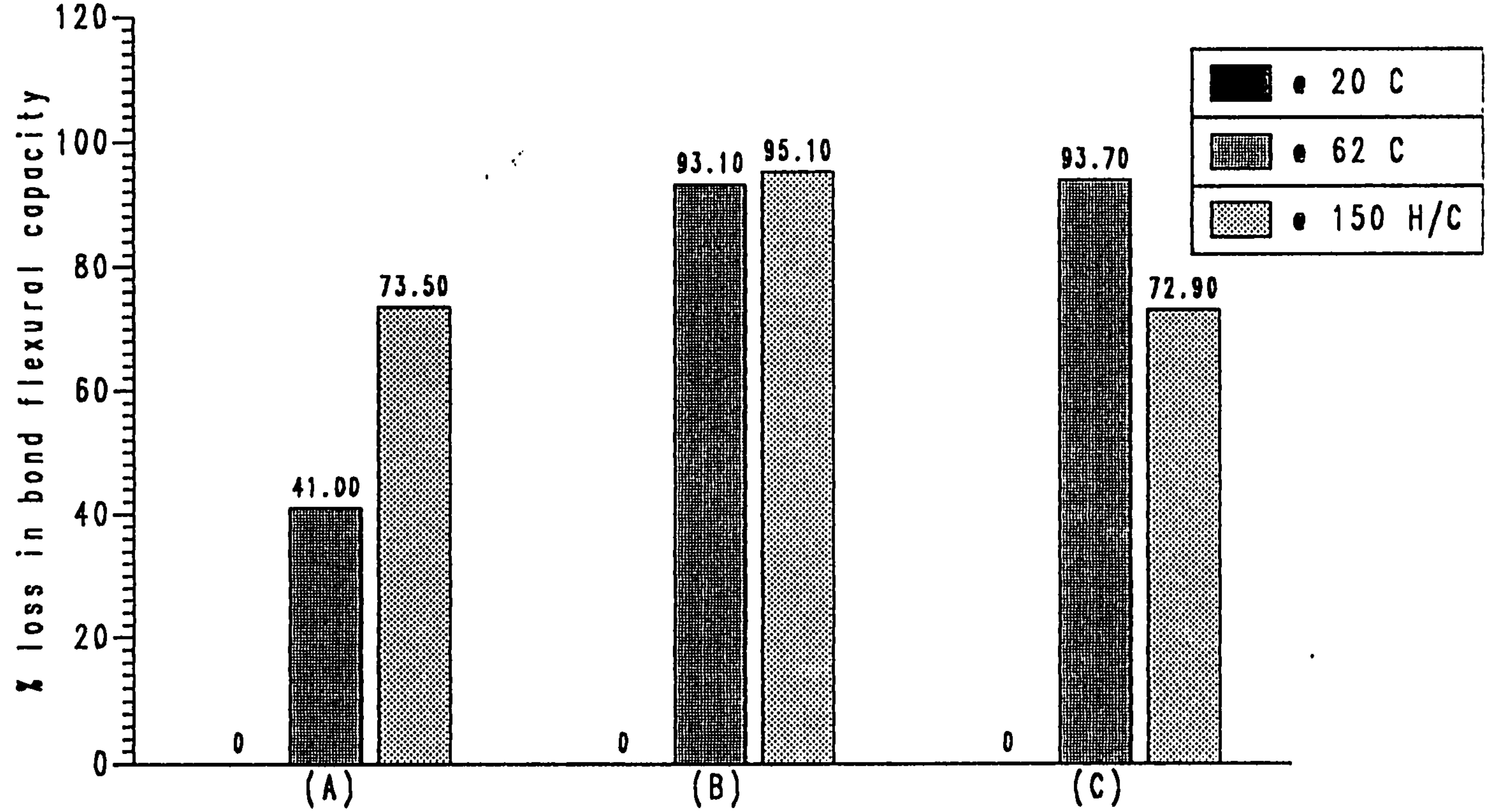


Table 4.18: Percentage Loss in Bond Flexural Capacity Between Epoxy and Concrete in Beams due to High Temperature and H/C Cycling (in terms of the Bond Flexural Capacity at Normal Conditions)

Specimen Type	Normal Conditions	@ 62°C (143.6°F)	@ 150 H/C Cycles
Cracked Repaired with epoxy A (A)	0	41.0	73.5
Cracked Repaired with epoxy B (B)	0	93.1	95.1
Cracked Repaired with epoxy C (C)	0	93.7	72.9

Fig. 4.21: Comparison of the Effects of Temp. & H/C Cycling on the Epoxy-concrete Bond In Beams (in terms of Bond Capacity @ 20 C)



We notice in Figs. 4.21 and 4.22 that the bond between epoxy A and concrete was affected adversely more due to H/C cycling program than due to the exposure to high temperature of 62°C (143.6°F), when repaired beams were tested in flexure. In contrast, the bond between epoxy C and concrete was affected adversely more due to temperature than due to H/C cycles. Epoxy-concrete bond in the case of epoxy B showed comparable degradation due to either of the exposure to high temperature or the exposure to large number of H/C cycles.

Therefore, we conclude from the above tables and figures that the exposure to high temperature levels or to a large number of H/C cycles had a drastic effect on the flexural strength of epoxy-injected repaired beams. We would expect a larger reduction in the strength of these repaired beams if the two environmental conditions were applied together to the beams, particularly if the specimens were loaded in the same time, a case which is common in the field for the repaired structures subjected to severe environmental conditions.

4.6.2 Results of Repaired Cylinders

A comparison of the effects of temperature, H/C cycling and W/D cycling on the performance of repaired cylinders is presented here in a manner similar to that of repaired beams.

Table 4.19 and Fig. 4.22 show the ultimate applied loads (kN) at normal conditions (20°C = 68°F, 0 cycles) as well as 63°C

Table 4.19: Comparison of the Effects of Temperature, H/C Cycling and W/D Cycling on the Compressive Strength of Epoxy-Injected Repaired Cylinders

Specimen Type	Ultimate Applied Load (kN)			
	Normal Conditions	@ 63°C (145.4°F)	@ 316 H/C Cycles	@ 120 W/D Cycles
Solid Cracked (S)	222.6	244.0	218.3	260.8
Cracked Repaired with epoxy A (A)	172.7	19.0	207.0	186.5
Cracked Repaired with epoxy B (B)	101.0	17.8	173.5	46.8
Cracked Repaired with epoxy C (C)	181.5	16.2	208.3	110.3

Fig. 4.22: Comparison of the Effects of Temp. , H/C & W/D Cyclings on the Compressive Strength of Epoxy-injected Repaired Cylinders

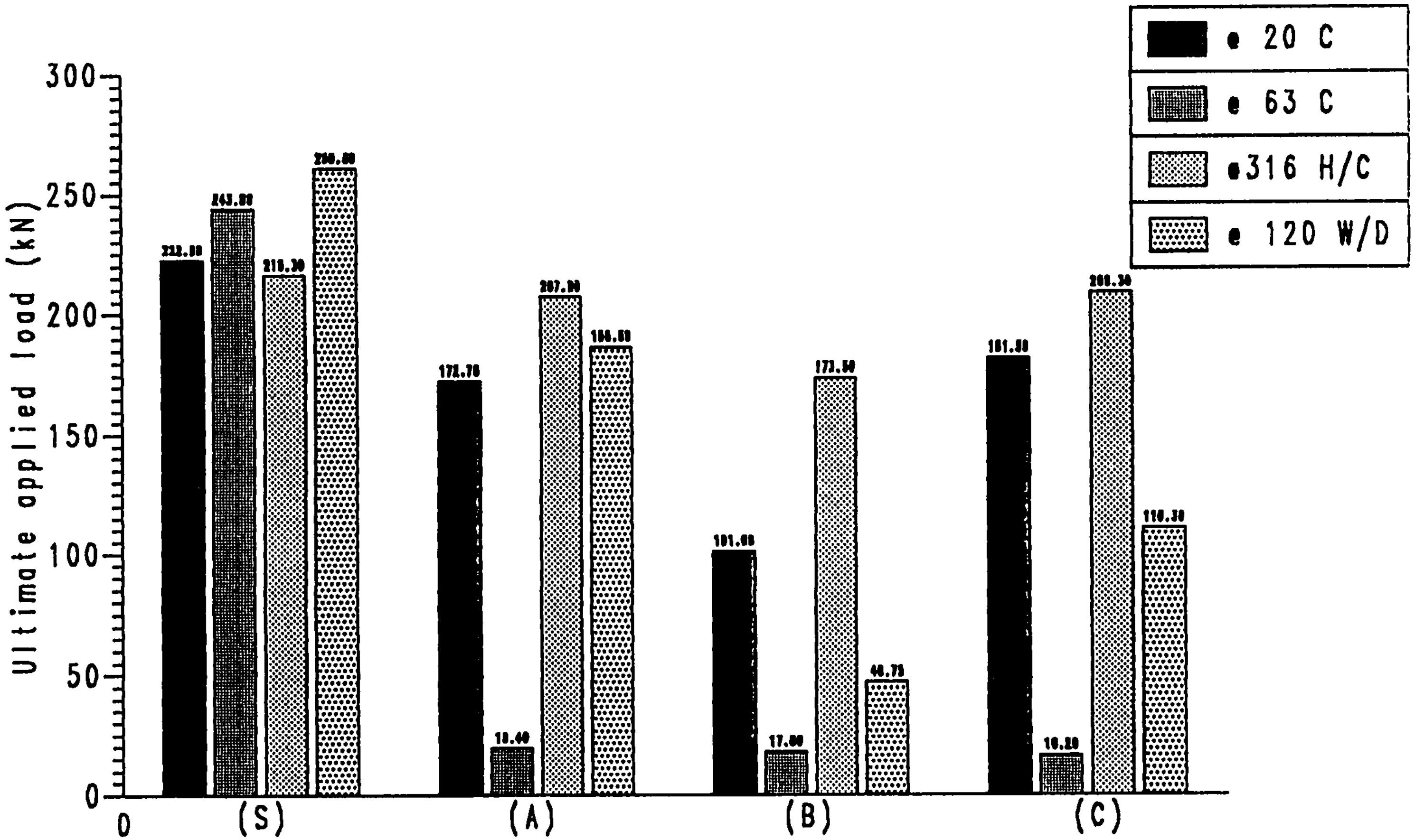


Table 4.20: Comparison of the Effects of Temperature, H/C Cycling and W/D Cycling on the Compressive Strength of Epoxy-Injected Repaired Cylinders (as Percentage of the Solid Cylinder Values)

Specimen Type	Ultimate Applied Load (%)			
	Normal Conditions	@ 63^{0}C (145.4^{0}F)	@ 316 H/C Cycles	@ 120 W/D Cycles
Solid Cracked (S)	100.0	100.0	100.0	100.0
Cracked Repaired with epoxy A (A)	77.6	8.0	94.8	71.5
Cracked Repaired with epoxy B (B)	45.4	7.3	79.5	17.9
Cracked Repaired with epoxy C (C)	81.5	6.6	95.4	42.3

Fig. 4.23: Comparison of the Effects of Temp. , H/C @ W/D Cyclings on Compressive Strength of Repaired Cylinders (as % of (S) Value)

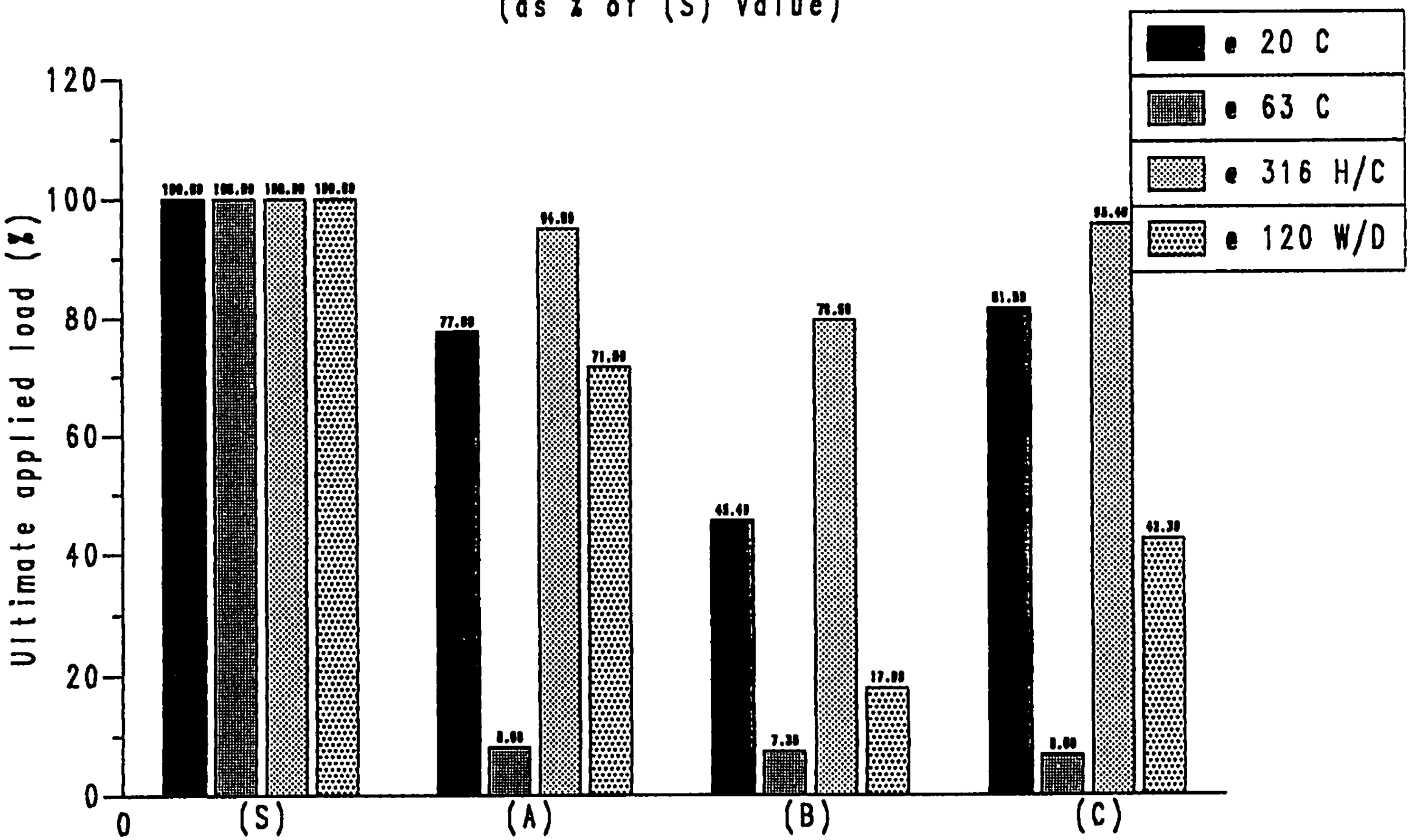
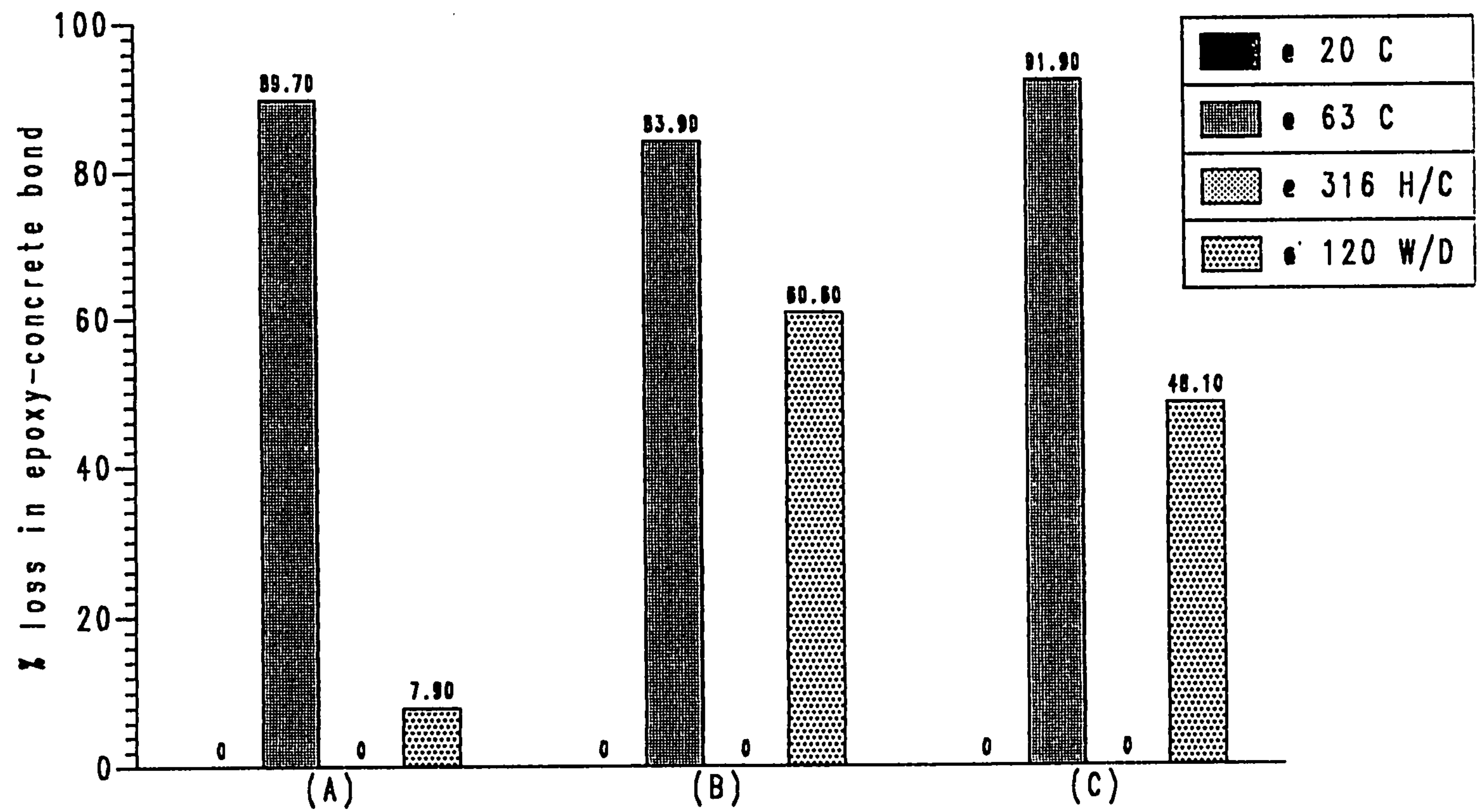


Table 4.21: Percentage Loss in Epoxy-Concrete Bond under Combined Shear and Compressive Stresses in Cylindres due to high temperature, H/C Cycling and W/D Cycling (in terms of the Bond Capacity at Normal Condition)

Specimen Type	Normal Conditions	@ 63°C (145.4°F)	@ 316 H/C Cycles	@ 120 W/D Cycles
Cracked Repaired with epoxy A (A)	0	89.7	--	7.9
Cracked Repaired with epoxy B (B)	0	83.9	--	60.6
Cracked Repaired with epoxy C (C)	0	91.9	--	48.1

Fig. 4.24: Comparison of the Effects of
Temp. , H/C @ W/D Cyclings on The Bond in Cylinders.
(in terms of Bond Capacity @ 20 C)



(154.4°F), after 316 H/C cycles, and after 120 W/D cycles for each type of cylinders (S), (A), (B) and (C). Table 4.20 and Fig. 4.23 present the same data as percentages of the solid cylinder values tested under similar conditions. Percentage losses in bond capacity of the three epoxy products used are shown in Table 4.21 and Fig. 4.24 in terms of the reduction in ultimate applied loads to cylinders as a result of the various factors mentioned above.

From these figures we notice that all epoxies were affected adversely and considerably at 62°C (143.6°F). The performance of the three epoxy products was quite comparable at this temperature level. Cylinders repaired with these epoxies lost almost 90% of their compressive strength due to the softening of the epoxy products and the damage in bond between these epoxies and concrete in addition to the thermal stresses developed along the bond interface. The second damaging factor on the performance of these epoxies is the W/D cycling as seen from the results. The three epoxies used showed a variation in the extent of damage due to this factor. Although W/D cycling changed the mode of failure of these cylinders from the conic concrete failure to the slant shear failure through the bond plane, the loss in bond between epoxy and concrete, and accordingly the loss in the ultimate applied load, was not of the same magnitude. Epoxy product A, being the lowest affected, lost about 10% of its bonding capacity as compared to its capacity before cycling. Epoxy product B, being the highest affected, lost almost 60% of its bonding capacity, while epoxy C has got a value in between these two values at about 50%. H/C cycling program described before seemed to be insufficient to reflect the adverse effect of such factor on repaired cylinders. The bond between epoxy and concrete did not fail after the exposure to the specified number of H/C cycles. However it is believed that at higher number of H/C cycles or the use of more severe cycling program the adverse effect, which appeared in the results of repaired beams, would be detected.

It is believed that these environmental factors, namely high temperature, H/C and W/D cyclings, would be more severe and harmful on repaired elements when combined together, particularly if they were applied while repaired elements were under some type of loading. In fact structures in the region of the Arabian Gulf area are subjected to such type of combination, which makes the durability of repair materials in this region a problem that requires carefully studied solutions.

The behavior of epoxy-concrete bond under various environmental conditions, as tested by the slant shear test specimens, can be examined analytically based on limit analysis of plain concrete [48] as follows:

For a cylindrical specimen of diameter d under applied compressive stress σ (Fig. 4.25), AA' is a plain construction joint of an angle β with the horizontal. Failure along the construction joint will take the form of a plane-displacement field. We select a failure mechanism whereby the upper part of the concrete cylinder is

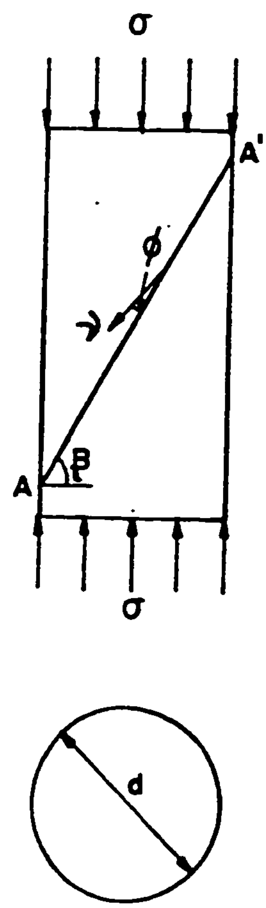


Fig. 4.25: Construction Joint under Uniaxial Compression

displaced υ in relation to the lower part. As this is a case of a plane displacement field, the angle between υ and AA' must be greater than or equal to φ, that is pure sliding failure, where φ is the angle of internal friction.

With the displacement field adopted, the work applied by the external stress is:

$$W_E = \sigma\upsilon \sin(\beta - \varphi) \frac{\pi}{4} d^2 \tag{4.1}$$

The internal-energy dissipation in the line of discontinuity is found to be

$$W_I = \upsilon C \cos\varphi \left(\frac{1}{\cos\beta} \frac{\pi}{4} d^2\right) \tag{4.2}$$

where C is the cohesion. Equating W_E to W_I yields

$$\sigma = \frac{2C \cos\varphi}{\cos\beta \sin(\beta - \varphi)} \tag{4.3}$$

If there were no construction joints, β could be varied. Minimizing Eq. (4.3) with respect to β, a minimum would be obtained for $\beta = \frac{\pi}{4} + \frac{\varphi}{2}$ and we get

$$\sigma_{min} = \frac{2C \cos\varphi}{1 - \sin\varphi} = f_c' \tag{4.4}$$

which is the uniaxial compressive strength. When there is a construction joint, there may be a lower cohesion C in the joint than in monolithic concrete. The angle of friction often proves to be the same as long as the faces of the construction joint are made reasonably rough. Tests show that the angle of friction of concrete turns out to be nearly a constant $\varphi \approx 37^{0}$. It should be noted that if Eq. (4.3) gives a value of $\sigma > f_c'$, failure will occur in monolithic concrete outside the construction joint for $\sigma = f_c'$ as in Eq. (4.4).

Let us now consider the group of cylinders tested at normal conditions of 20^{0}C and 0 cycles. The solid unrepaired cylinders have failed by the crushing of concrete under an average applied load of 222.6 kN. This is equivalent to 48.8 N/mm^2 (7.08 ksi) which is the ultimate compressive strength of concrete f_c'. Substituting this value in Eq. (4.4), and taking $\varphi = 37^{0}$ results in the value of cohesion C = 12.2 N/mm^2 (1.77 ksi). Turning our attention to the repaired cylinders, we find that cylinders repaired with epoxies A, C have got their failure in concrete away from the repair surface indicating a cohesion value C of the epoxy-concrete bond greater than that of monolithic concrete. However, that was not the case with cylinders repaired with epoxy B. They failed in shear through the bonding plane between epoxy and concrete indicating a lower value of cohesion C. The value of the average applied load was 101.0 kN $\equiv$ 22.1 N/mm^2 (3.20 ksi), and by substitution in Eq. (4.3) in this case for $\sigma = 22.1$ N/mm^2 (3.20 ksi), and $\beta = 60^{0}$, a value of

$C = 5.4 \text{ N/mm}^2$, (0.78 ksi) is obtained. This low value of C was due to the reasons mentioned previously in Section 4.4.2. Likewise, cylinders exposed to high temperature, heat-cool, and wet-dry cycling programs could be analyzed in the same way. Thus with the relation between C and σ known (Eqs. 4.3, 4.4), and if the reduction in C due to the given conditions is determined, the carrying capacity of a construction joint can be calculated.

4.6.3 Results of Repaired Beams Versus Repaired Cylinders

A comparison is made here between the performance of epoxy products used in beams and in cylinders. In the case of beams, epoxies were subjected to linear tensile stresses due to the applied flexural loading to beams, while they were subjected to combined shear and compressive stresses when the cylinders were loaded in compression as mentioned earlier (Section 4.2-4.5). Tables 4.18, 4.21 and Figs. 4.21, 4.24 can be used for this comparison. We notice that the performance of repaired beams and cylinders is similar at high temperature (62°C = 143.6°F, 63°C = 145.4°F), where most of the specimens strengths were lost due to the degradation of the epoxy concrete bond at these high temperatures. Losses were in the vicinity of 90%, except in the case of beams repaired with epoxy A where a lower value was obtained. Heat-cool cycling did affect the repaired beams adversely resulting in an average loss in the bond strength between epoxy and concrete of about 80%. However, heat-cool cycling program could not degrade the epoxy-concrete bond in the case of repaired cylinders, and a more severe or prolonged program is needed to show the effect of this factor on the long run. Finally wet-dry cycling was applied to cylinders and resulted in different levels of degradation in their bond strengths for different types of epoxies used, with about 10% and 60% as minimum and maximum percentage losses after 120 W/D cycles in terms of their bonding capacities at normal conditions and according to the results of H/C cycling program, it is expected that such W/D cycling process would affect repaired beams severely when applied to it, even more than the H/C cycling process.

4.6.4 *Comparison of the Flexure (Beam) Model versus the Compression* (Cylinder) Model

The concrete beam specimens used in this study (Fig. 2.9) were adopted from an earlier model suggested by Fattuhi [23, 24, 25], but with larger dimensions. These beam specimens with the adopted dimensions have clearly reflected the variation in the epoxy bonding capacity to concrete as it was subjected to the various environmental conditions. Careful preparation of the crack surface was required in order to obtain reliable results. The artificially induced cracks constitute a poor representation of real concrete cracks, this is due to their smooth surface and their large widths (1.6mm = 1/16 in) when compared to actual cracks. Fattuhi mentioned that preliminary investigations showed that the width of the beam crack is critical when hand injection is used since viscosity of the different repair materials varies considerably [23], and accordingly a smaller thickness can be used. In practice it is recommended to have the thickness of the bonding layer as thin as possible in order to get a durable repair. However, using a thickness of 1.6mm (1/16 in) can be looked at as a way of exaggerating the behavior of the bonding layer under the applied conditions. With this thickness the trend of the results of the beam specimens has clearly reflected the effects of environmental factors considered in this study.

Furthermore, the crack was made on the beam specimen by inserting a notch of the same thickness during casting so that different beams would have cracks with the same geometry, which allowed the study and comparison of different factors and materials under consideration. It would be valuable to study the relation between the results of the beam specimen used here and the results of the actual behavior of epoxy-injected natural crack in concrete.

An interesting variation to these beam specimens would be to allow the simulated crack to extend the whole depth of the beam (Fig. 4.26). Although it requires more repair material and work, this variation allows better control over the crack thickness as well as better surface preparation; e.g., acid etching or sand blasting. Another variation is to let the crack outside the middle third of the beam, where the epoxy-concrete bond will be subjected to combined shear and linear tensile stresses instead of linear tensile stresses only.

The concrete cylinder specimens utilized in this work (Fig.

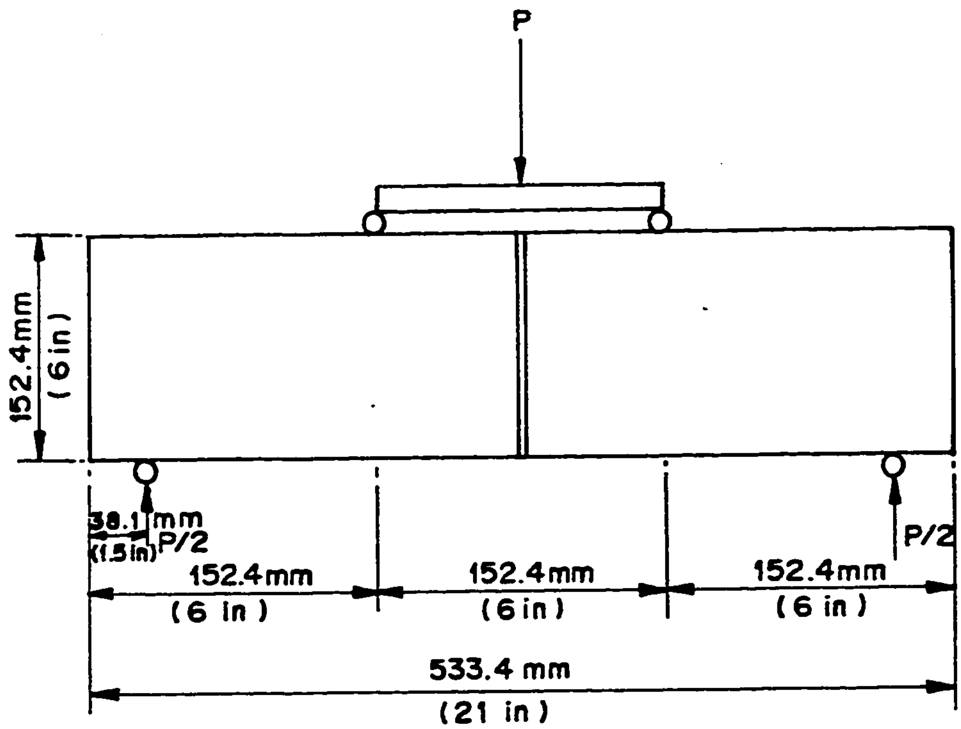


Fig. 4.26: The Beam Specimen with the Middle Crack Extending the Whole Depth of Beam

2.8) were similar to those described in ASTM C-882, but made up of concrete and of a crack width of 1.6mm (1/16 in) with its surfaces roughened by sand blasting (Section 2.2.2). Repaired cylinder specimens could reflect the adverse effect of temperature and wet-dry cycling on the bond strength between epoxy and concrete under combined compression and shear stresses. On the other hand, it did not show the degrading effect of the heat-cool cycling process on the bonding behavior of epoxies within the specified cycling program. That was justified by the strong shearing resistance of the epoxy material enhanced by the frictional force resulting from the compression component of the applied loads on the epoxy-concrete interface and by having the crack surface rough, and therefore, it was believed that a more severe cycling program would reflect the adverse effects of that factor.

The method used in the preparation of repaired cylindrical specimens was difficult in preparing the cracked cylinders for epoxy-injection. A more accurate procedure for the preparation of this right cylinders is needed. The argument about the thickness and the crack surface for the beam specimen is applicable here also with the fact that the crack surfaces in the case of the cylinder specimens are more rough due to systematic sand blasting of these surfaces before repair. Finally, another technique such as that described by BS 6319:Part 4:1984 [21] might be easier and more efficient [(see Section 2.1.4(2)].

Since the shear properties of the adhesive are the most worthy of investigation if its useful strength is required [(Section 2.1.4(2)], it would be beneficent to study the bond response to the severe conditions considered here when it is subjected to pure shear. Although an elaborate set-up is required if turning moments and tensile stresses are to be avoided, a push-off specimen like that used by Chung and Lui [29, 30] is suggested to be used for this purpose. They carried out static and dynamic shear tests on concrete push-off specimens which were severely damaged and then repaired by epoxy injection. The specimen measured 125mm x 200mm (5 in x 8 in) in cross-section and 660mm (26 in) in length (Fig. 4.27). It is composed of two parts: a precast part and a cast-in-place part which was subsequently added. The interface between the two parts, 150mm (6 in), was a rough surface produced by exposing the coarse aggregate on the precast part by water washing before the concrete had set. A series of specimens had no reinforcement across the joint, while in another series there were two 5mm diameter mild steel stirrups provided across the joint [29].

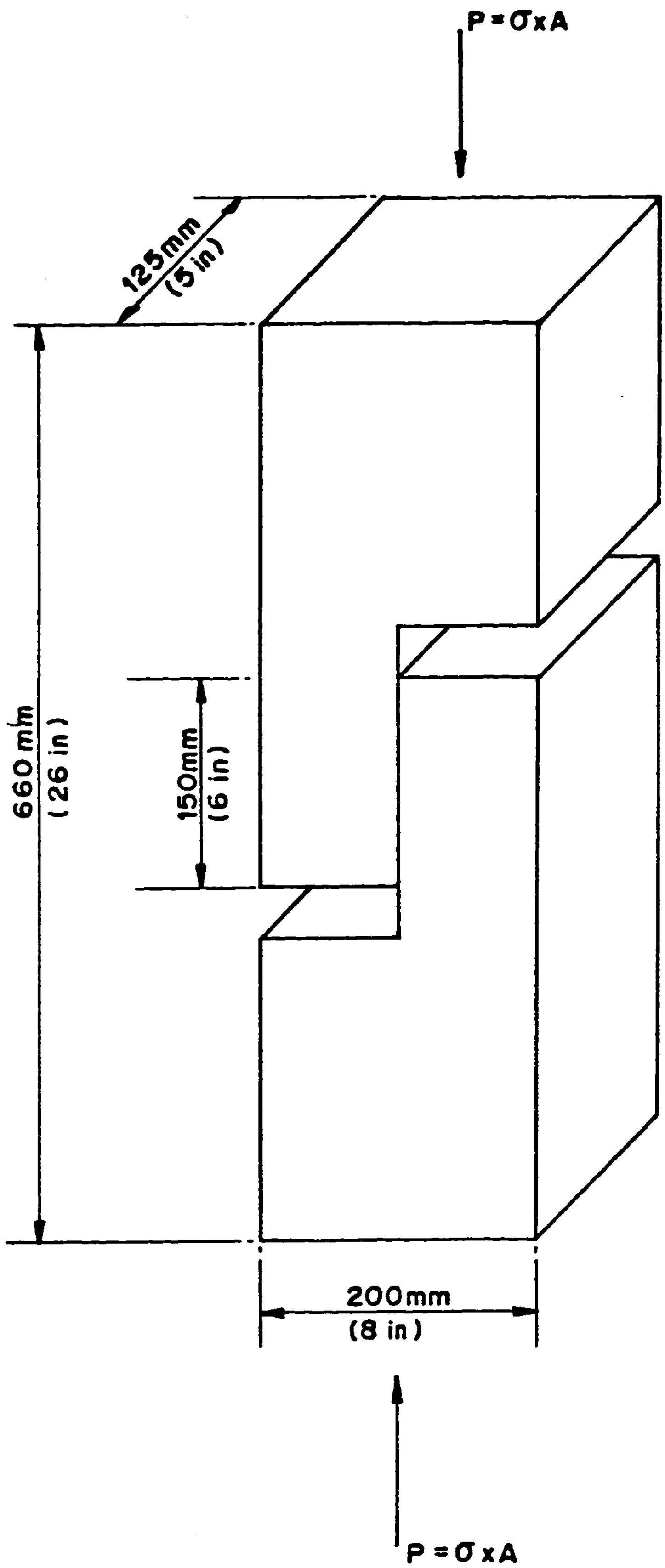


Fig. 4.27: The Push-off Specimen for Testing the Epoxy-Concrete Bond in Pure Shear.

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

This study was intended to examine and evaluate the performance of epoxy-injected concrete elements under severe environmental conditions characterized by the exposure to high temperature, and seasonal and diurnal variations of temperature and humidity. An experimental program was established in which pre-cracked concrete beams and cylinders were epoxy-injected using three different and locally available epoxy products. Beam specimens were exposed to a high temperature condition, and a heat-cool cycling program and then tested in flexure, where the bond surfaces between epoxy and concrete were subjected to flexural tensile stresses. Cylindrical specimens were exposed to a high temperature condition, heat-cool cycling, and wet-dry programs, and then tested in compression, where the bond surfaces between epoxy and concrete were subjected to combined compressive and shear stresses.

5.2 Conclusions

Based on the outcome of this study, the following conclusions are drawn:

1) Epoxy adhesives A, B and C perform well in repairing concrete under normal environmental conditions.

2) Behavior of epoxy-injected concrete on the long run and under actual surrounding conditions is of equal importance to its behavior under normal conditions.

3) High temperatures degrade the epoxy-concrete bond considerably. Epoxy products A, B and C lost around 90% of their bonding strength to concrete when tested at 62.5°C (144.5°F) regardless whether the bond interface is subjected to tensile or combined compressive and shear stresses (except that beams injected with epoxy A showed a smaller percentage of loss in bond).

4) The softening of the epoxy products and the change in thier properties at high temperatures in addition to the development of high thermal stresses at the. bond interface as a result of the difference between their coefficients of thermal expansion and that of concrete lead to this considerable reduction in the strength of repaired concrete elements.

5) Repetitive heat-cool cycling of repaired concrete elements results in a considerable reduction in the bonding strength of epoxies to concrete. An average of 80% loss in the bond strength of epoxy to concrete was obtained after 150 H/C cycles when the bond was subjected to linear tensile (flexural) stresses.

6) Epoxy-concrete bond showed a resistance to the heat-cool cycling process of 316 cycles or less when it was subjected to combined compressive and shear stresses. Larger number of H/C cycles or more severe H/C cycling program is believed to be required in order to show its adverse effect on bond.

7) The repetitive development and release of thermal stresses resulting from the heat-cool cycling process due to the difference in coefficients of thermal expansion beteween epoxy and concrete leads to fatigue in the bond line interface between epoxy and concrete and failure can occur at even lower values of stress.

8) Repetitive wet-dry cycling has a severe adverse effect on the epoxy bond to concrete. Epoxy products A, B and C showed different levels of degradation after 120 wet-dry cycles of about 10%, 60% and 50% losses in their bonding capacities when the epoxy-concrete bond weas subjected to combined compressive and shear stresses, respectively, compared to those without cycling.

9) The repetitive stresses resulting from the frequent changes in temperature and from the differences in volume changes between epoxy and concrete during the frequent moisture movement into and from repaired concrete during the wet-dry cycling process result in fatiguing the epoxy-concrete bond and lead to the shear failure of repaired

cylinders at lower loads.

10) The above mentioned factors will be more severe to repaired concrete elements when they are combined together, particularly if they are applied while repaired elements are subjected to some type of loading.

11) Thus the Arabian Gulf environment adversely affects the bonding capacity of epoxies used in repairing concrete.

12) The performance of epoxy compounds under such adverse conditions depends on their characteristics related to these conditions such as their phase changes or transition temperatures, their coefficients of thermal expansion, their creep characteristics, their moduli of elasticity, the maximum permissible service temperature, and their ability to resist humidity and wetted concrete.

13) Repaired beam specimens could reflect the adverse effect of temperature and heat-cool cycling on the bond strength between epoxy and concrete in general and under flexural strength in particular. Dimensions of the beam specimens were adequate enough to provide a sufficient range for the variation of the ultimate applied load under conditions such as those considered in this study. However, careful preparation of the crack surfaces is required in order to obtain reliable results.

14) Repaired cylinder specimens could reflect the adverse effect of temperature and wet-dry cycling on the bond

strength between epoxy and concrete under combined compressive and shear stresses, but it did not show the degrading effect of the heat-cool cycling process and a more severe cycling program is needed to show this effect.

15) The method used in the preparation of repaired cylindrical specimens was rather difficult in preparing the cracked cylinders for epoxy injection. A more accurate procedure for the preparation of these right cylinders is needed. Another technique such as that described by BS 6319:Part 4:1984 might be easier and more efficient.

5.3 Recommendations

1) This study has proven the degradation of epoxy-injected repaired concrete elements under severe environmental conditions characterized by high temperature exposure, heat-cool and wet-dry cycling processes. Since these conditions are compatible to actual conditions in the Arabian Gulf region and Saudi Arabia, caution must be exercised in the use of epoxy products to restore the structural integrity and durability of building components that are exposed to such conditions.

2) In order to achieve a successful repair process, it is necessary to choose the most suitable technique. select the most proper repair material, follow the manufacturer

instructions, and achieve the repair process successfully.

3) Further experimental work is needed to examine, evaluate and solve the strength and durability problems of repair by epoxy-injection. Using reinforced concrete elements, studying actual cracks, dealing with different thicknesses, considering the combined action of different environmental conditions, applying different patterns of loading to the epoxy concrete bond such as pure shear stresses, combined shear and tensile stresses, etc., and using a variety of epoxy materials are some of the factors that should be considered in future programs.

4) The beam and cylinder specimens used in this study can be utilized in the further experimental work needed in this field. Push-off specimens may also be used for studying the bonding behavior of epoxies in pure shear under different surrounding conditions.

5) Based on a detailed study, local specifications should include certain criteria on the epoxies used in the Arabian Gulf area and Saudi Arabia so that durability of repair works with these materials is assured in the severe surrounding environment. A set of standard test methods is also needed so that suppliers as well as users can use them in the evaluation of the performance of epoxy products to meet such criteria.

6) A set of properties to define the behavior of these epoxy

compounds in the region is required to be added to the list of properties provided in the manufacturer data and instruction sheets to help in the selection of the most proper repair material for a given job.

7) Epoxy products specially made to suit the local conditions should be the only types to be supplied and used in the local market.

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